COMSAT Laboratories

Task 5 Final Report

NASA CR-168058

PLANNING ASSISTANCE FOR THE NASA 30/20-GHz PROGRAM

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NETWORK CONTROL ARCHITECTURE STUDY

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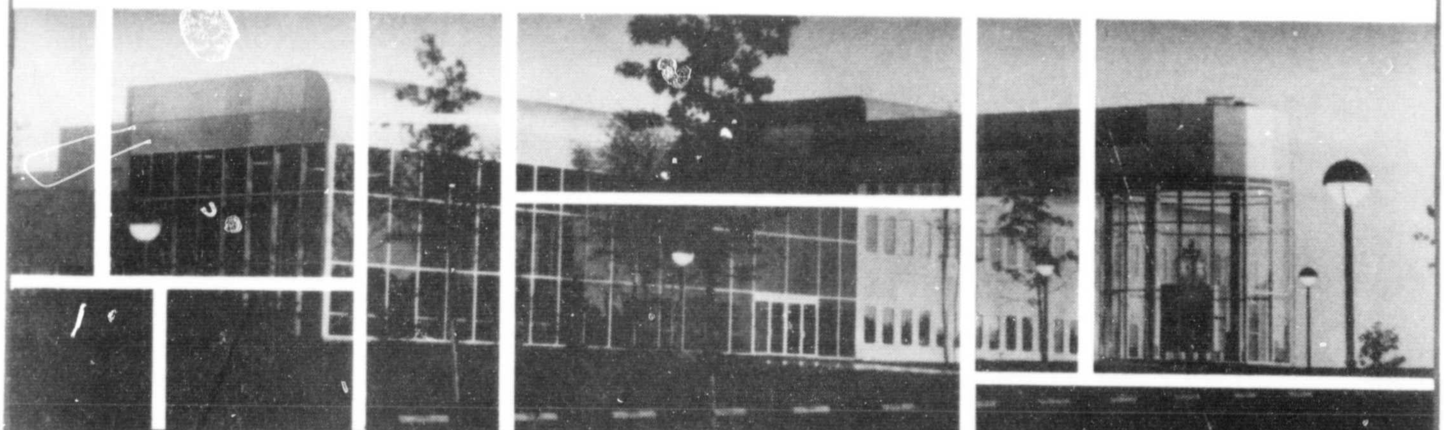
COMMUNICATIONS SATELLITE CORPORATION
COMSAT Laboratories Clarksburg, Maryland 20871



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NASA Project Manager: T. Coney
NASA Lewis Research Center
Cleveland, Ohio 44135

COMSAT General Project Manager
C. Devieux
Washington, D.C. 20024

16. Abstract

This report describes the study of the Network Control Architecture for a 30/20 GHz flight experiment system operating in the Time-Division Multiple Access (TDMA). It covers architecture development, identification of processing functions, and performance requirements for the Master Control Station (MCS), diversity trunking stations, and Customer Premises Service (CPS) stations. Preliminary hardware and software processing requirements as well as budgetary cost estimates for the network control system are given. For the trunking system control, areas covered include on-board SS-TDMA switch organization, frame structure, acquisition and synchronization, channel assignment, fade detection and adaptive power control, on-board oscillator control, and terrestrial network timing. For the CPS control, they include on-board processing and adaptive forward error correction control.

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FOREWORD

This report presents the results of the study of "Demonstration System and Control Requirements," performed under Task 5 of the NASA Contract with COMSAT General, NAS-5-22905, "Planning Assistance for the 30/20-GHz Program." The period of performance was from March 1981 to March 1983.

The COMSAT General project manager for the Planning Assistance Contract is Dr. Carrie L. Devieux, Jr. The Network Control Study (Task 5) was performed for COMSAT General by COMSAT Laboratories under project support authorization Task No. STS-81-006.

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1. INTRODUCTION

The objective of the Network Control Architecture Study is to develop a time-division multiple-access (TDMA) network control system architecture for the 30/20-GHz experimental communications satellite system. The task covers network architecture development, identification of processing functions, and performance requirements for the Master Control Station (MCS), trunking stations, and customer premises service (CPS) stations. Based on the results of these investigations, hardware and software processing requirements and budgetary cost estimates for the network control system are generated.

The approach taken in the network control architecture design allows for the planned expansion of the experimental system into an operational one. Thus, the proposed architecture not only satisfies the requirements for planned experiments, but also can accommodate a possible operational network with a larger number of earth stations and complex network control functions. This expansion can be achieved by modifying the system parameters of the TDMA frame structure.

The organization of this report is as follows. Section 2 describes the network control system requirements for the experimental system. Control subsystems and processing functions are also identified. Section 3 presents a detailed network control architecture for the trunk system, including considerations of IF switch-state organization, frame structure, acquisition and synchronization, channel assignment, fade detection and adaptive power control, on-board oscillator control, and terrestrial network timing.

Section 4 is dedicated to the CPS network control architecture. The basic control system is similar to that of the trunk network; however, special consideration is given to the on-board baseband processing requirements and adaptive forward-error-control (FEC) techniques. The majority of the CPS network users directly access the space segment at the customer premises earth station, and special interface units are required between the subscriber terminal equipment and the earth station baseband interface. Various types of network interfaces are discussed.

Section 5 presents the study results of the ground terminal configuration. The RF equipment, TDMA baseband equipment, and terrestrial interface equipment configurations are discussed in detail for the MCS, trunking stations, and CPS stations. Hardware and software processing requirements and equipment lists are given, as well as a description of the network operations center (NOC) data processing functions at the MCS.

Section 6 provides budgetary cost estimates (in 1982 dollars) for the network control system. Section 7 presents conclusions and recommendations, and Section 8 supplies references.

2. NASA 30/20-GHz NETWORK CONTROL REQUIREMENTS

2.1 EXPERIMENTAL SYSTEM DESCRIPTION

The experimental satellite communications payload consists of an SS-TDMA system for high-data-rate trunking services and an on-board baseband processing system for low-data-rate customer premises services. The beam coverage of the experimental system is shown in Figure 2-1.

The trunk network is composed of six fixed spot beams or nodes with only four simultaneously active beams: Cleveland, Los Angeles, New York, and Washington, D.C. The two alternate nodes, Houston and Tampa, can be activated instead of New York and Washington, D.C., respectively. The trunk network employs the TDMA mode of access along with an on-board IF switch matrix for beam interconnection. The burst rate in each of the four active beams is nominally 256 Mbit/s, and the up-link and down-link frequencies are 30 and 20 GHz, respectively.

The CPS payload incorporates two independently steerable scanning beams covering two adjacent sectors in the eastern United States. Each sector is approximately 10 percent of CONUS and is assigned a pair of independently steerable and simultaneously active up-link and down-link beams. In addition, three spot beams at isolated locations, i.e., Seattle, San Francisco, and Denver, are generated by the beam-forming networks associated with the two scanning beams. The CPS up-link in each section consists of either four 32-Mbit/s TDMA channels or one 128-Mbit/s TDMA channel, and the transmitted bursts are demodulated, buffered, processed, and modulated by the spacecraft on-board baseband processor and transmitted to the designated areas in a

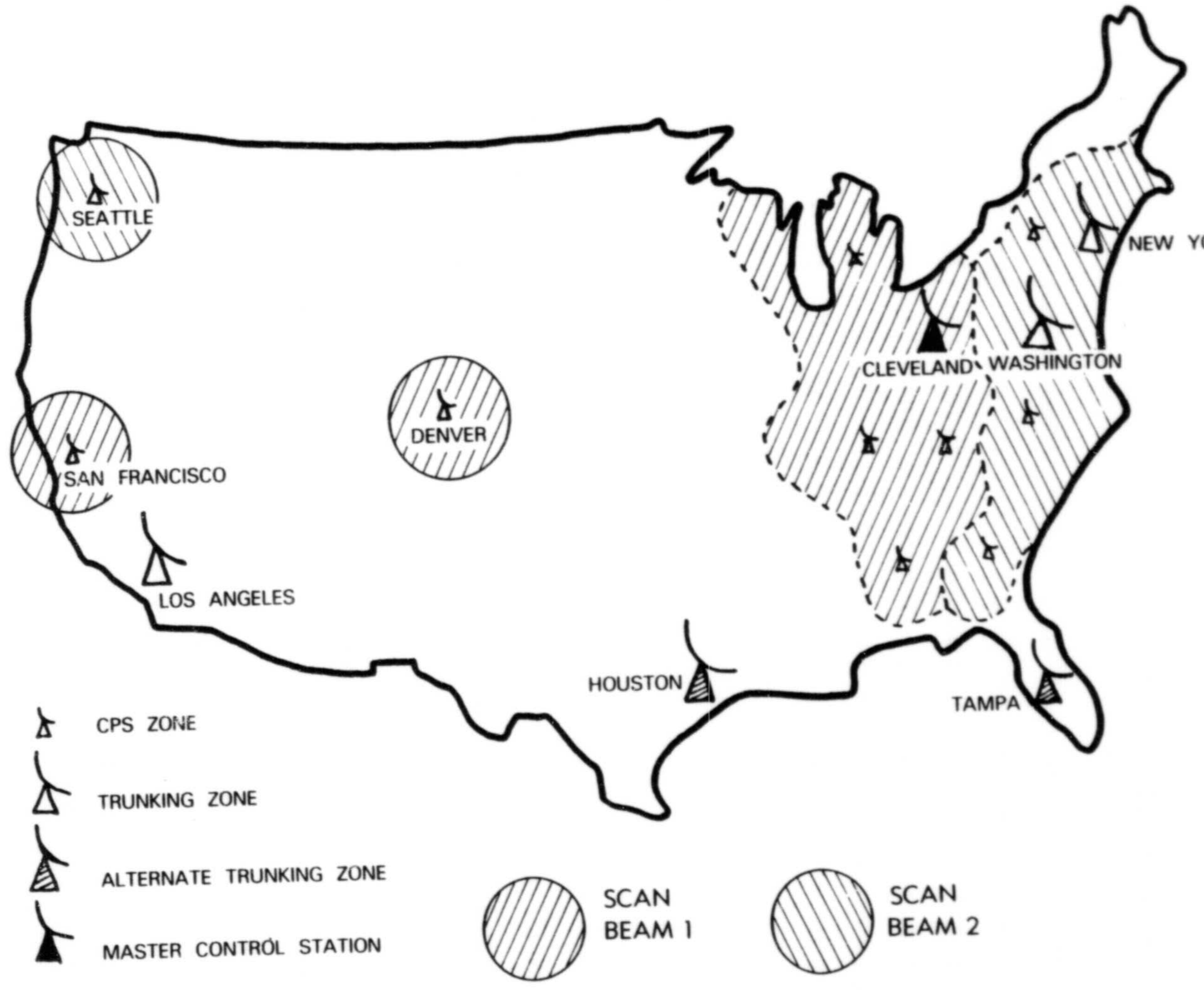

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Figure 2-1. Beam Coverage of the Experimental System single 256-Mbit/s down-link channel. Interconnection of cross-sector traffic is also accomplished by the on-board baseband processor. Each scanning beam uses the same frequency spectrum, and beam isolation is accomplished through orthogonal polarization and spatial separation. The operating frequency bands are the same as the trunking service payload, i.e., 30-GHz up-link, and 20-GHz down-link, and simultaneous trunking and CPS operation are not required.

2.2 NETWORK PARAMETERS

The trunk network consists of earth stations with a 5-m antenna and employs spatial diversity earth terminals and adaptive power control to combat a heavy rain fade. The rain fade margin is at least 18 dB for the up-link and 8 dB for the down-link, and is adaptively controlled by the Master Control Station (MCS) commands.

The CPS earth station antenna size is 3 m for the 32-Mbit/s up-link burst rate and 5 m for the 128-Mbit/s up-link. The required rain fade margin, 15 dB for the up-link and 10 dB for the down-link, is realized by a combination of on-board FEC coding/decoding and data rate reduction, and is also adaptively controlled by the MCS commands. Critical network parameters are summarized in Table 2-1.

The spacecraft will be located on the geosynchronous orbit at about 100° west longitude, and stationkeeping maneuvers will confine its orbital position to an accuracy of ±0.05° in both inclination and longitudinal drift. This results in the maximum distance variations of 74, 74, and 25 km in the north-south, east-west, and radial directions, respectively. Synchronization-related parameters such as range rate, differential range rate, and range variations are calculated from the spacecraft orbital position accuracy as shown in Table 2-2. The earth station buffer to absorb Doppler shift can easily be computed from the range variation and type of network synchronization employed.

Table 2-1. Experimental Network Parameters

	Trunk Network	CPS Network
Beams	Four fixed	Two scanning
Transmission Mode	SS-TDMA	TDMA with baseband processor
Earth Station Antenna Diameter	5 m	3 m (32-Mbit/s Up-link) 5 m (128-Mbit/s Up-link)
Burst Rate	256 Mbit/s	128 Mbit/s and 32 Mbit/s (Up-link) 256 Mbit/s (Down-link)
Modulation	QPSK	QPSK
Frame Period	1 ms	1 ms
Rain Margin	18 dB (Up-link) 8 dB (Down-link)	15 dB (Up-link) 10 dB (Down-link)
FEC Gain	None	7.4 dB (Up-link and Down-link)
Power Control	0 ~ 10 dB	None

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Table 2-2. Spacecraft Orbital Parameters

Location	100°W (Geostationary orbit)
Inclination	±0.05°
E-W Drift	±0.05°
Eccentricity	0.0003
Range Rate	1.32 m/s (4.4 ns/s)[a]
Differential Range Rate	0.63 m/s (2.1 ns/s)[a]
Range Variation	±21 km (±70 μs)[a]
Relative Range Variation[b]	±3 km (±10 μs)[a]

[a]These values are calculated from the stationkeeping accuracy.
[b]The maximum range variation relative to the range measured at the MCS location (Cleveland).

2.3 NETWORK CONTROL

Major network control elements are shown in Figure 2-2. Control of the earth station network and satellite communications payload is performed from the MCS located near Cleveland (or some other location). Channel assignments are made on a preassigned basis for trunking and on a demand basis according to a reservation scheme for CPS. The on-board baseband processor (BBP) has the capability of routing individual 64-kbit/s CPS channels.

A network control procedure must efficiently and reliably control the scanning beams, baseband processor, IF switch, and other on-board subsystems necessary for the operation of the experimental system. Furthermore, coordinated control of various spacecraft and ground control subsystems based on a common time base is vital for reliable network operation.

Major network control functions, which include network acquisition and synchronization, demand-assignment processing, rain fade control, and on-board processing, are performed from the MCS. Figure 2-3 illustrates network control functions and

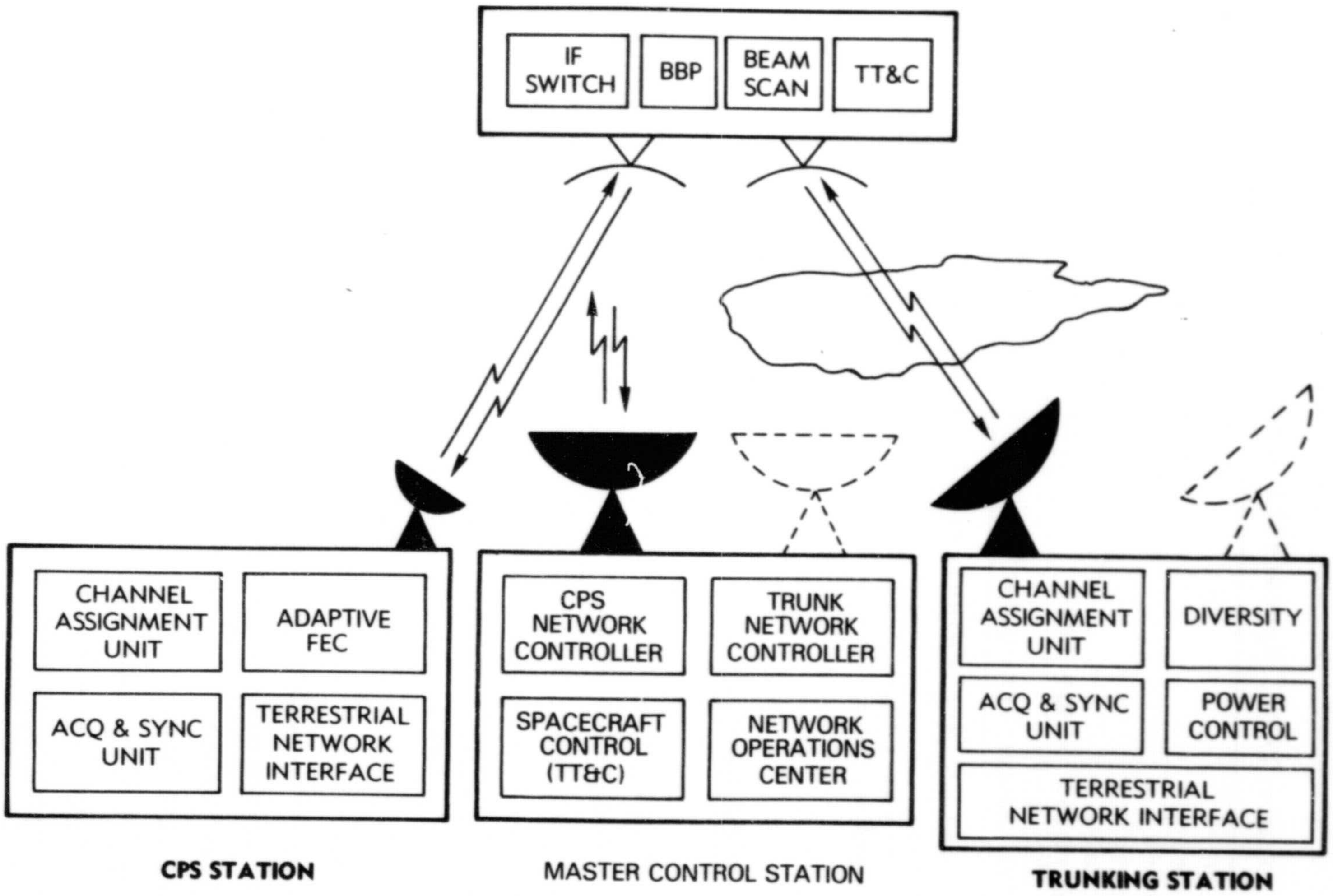


Figure 2-2. Network Control Subsystems

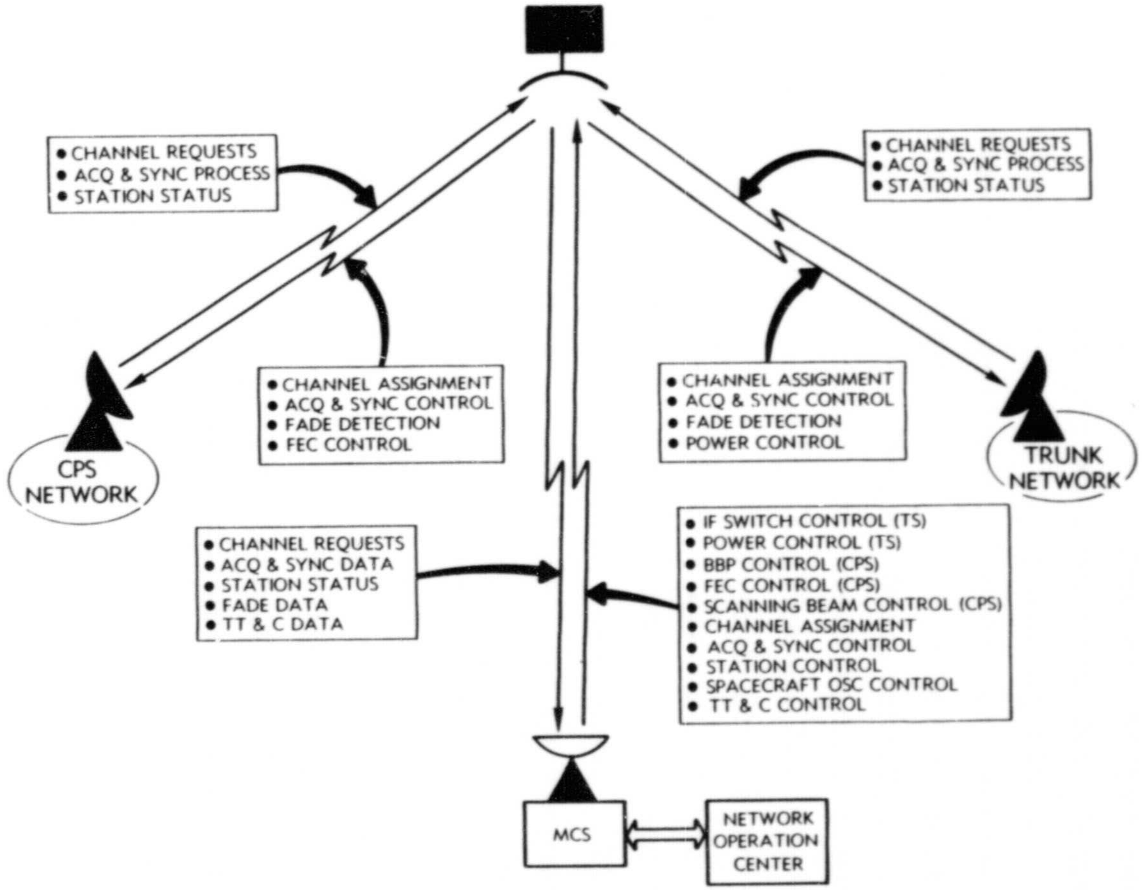


Figure 2-3. Network Control Functions

orderwire data required for the experimental system. The centralized control simplifies local earth terminal equipment and provides easy and rapid access to the network status data in order to monitor and control various network elements. In an operational system, redundant control stations are necessary to achieve highly reliable network operation.

The MCS performs the key role of controlling constantly changing network dynamics. Coordination between the MCS and network stations is established via orderwire channels. The orderwire data are transmitted on dedicated orderwire bursts or can be sent on the preamble field of traffic bursts. Communications between the MCS and spacecraft is accomplished by both orderwire channels and a TT&C data link.

The MCS consists of three major processing subsystems: the trunk network controller, the CPS network controller, and the local traffic processor. The first two subsystems are dedicated to data processing of time-critical orderwire data, whereas the third subsystem performs local traffic data processing. The two network controllers are not required to be simultaneously active. Non-time-critical orderwire data are transferred to the Network Operations Center (NOC) for processing. The NOC is responsible for overall network operation, traffic scheduling, open-loop acquisition timing computations, and other data processing functions that require large data bases.

3. TRUNK NETWORK CONTROL ARCHITECTURE

3.1 SATELLITE-SWITCHED TDMA

The satellite-switched TDMA (SS-TDMA) mode of operation is illustrated in Figure 3-1. It incorporates TDMA as a principal means of carrying network traffic and uses multiple beam antennas to achieve extensive frequency reuse. Interconnectivity among different beams is accomplished by a microwave switch matrix on the satellite, which allows TDMA traffic bursts transmitted in one beam to be routed to all others in a synchronous fashion as required by the network traffic plan. The switch configurations used for the beam interconnections are programmable and can be changed to optimize traffic flow.

The trunk network uses the same frequency band four times except for the Washington, D.C., beam which uses an adjacent frequency band (no frequency reuse). Switch configurations are initially computed by the MCS based on the network traffic requirements and sent to the satellite via the TT&C link. Switch-state timing is generated on board and has a TDMA frame period of 1 ms. A number of distinct switch states are generated during one frame period, and each transmitting station must synchronize its burst transmission to the on-board switch-state timing so that the transmitted bursts are routed to the desired down-beams. Multidestinational bursts may also be accommodated by implementing point-to-multipoint or broadcast switch connections on the satellite. This feature simplifies network control and provides efficient broadcast data transmission.

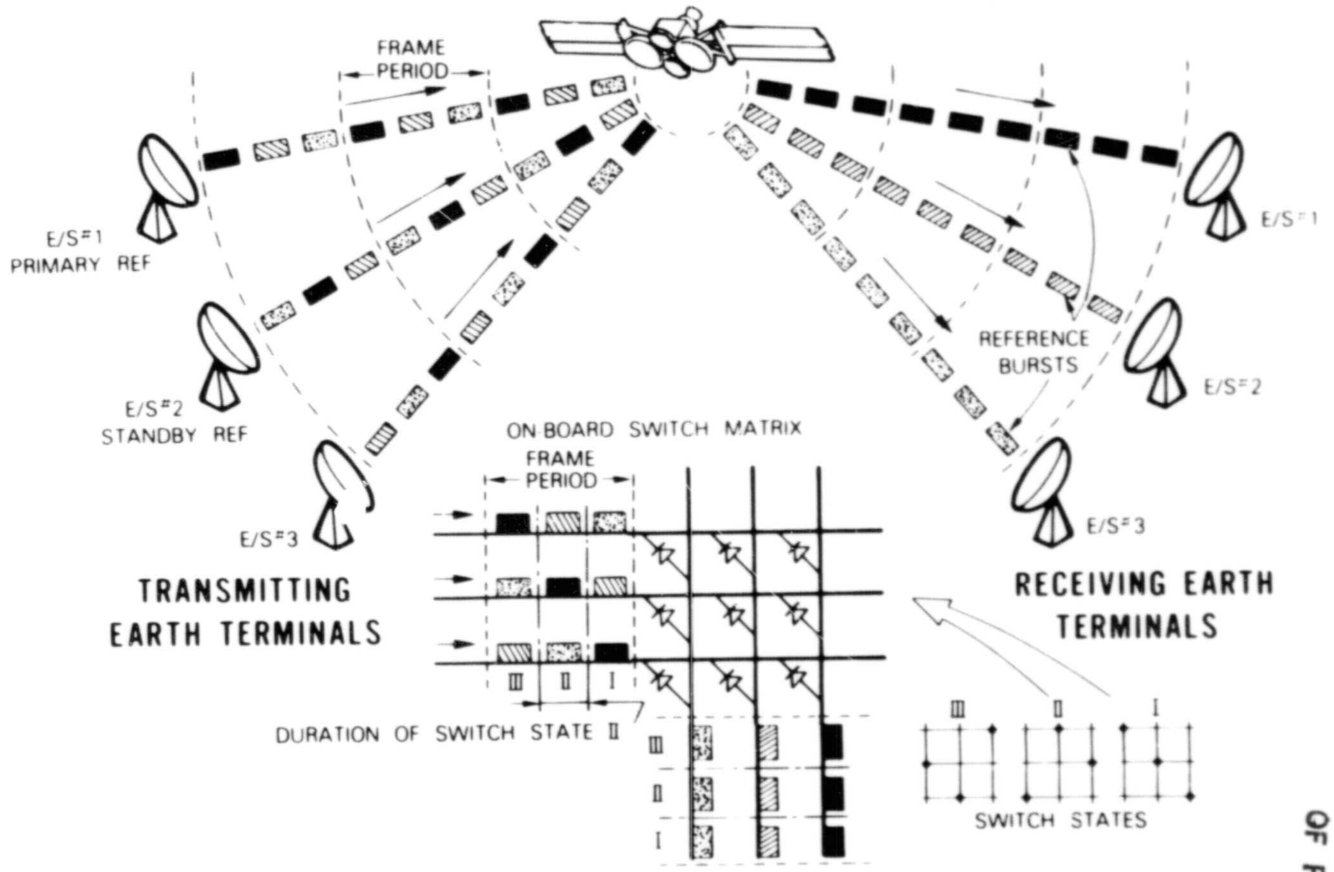


Figure 3-1. Typical Satellite-Switched TDMA System Operation

3.2 SWITCH-STATE ORGANIZATION

A TDMA frame length is 1 ms long and is composed of a synchronization window, a reference burst window, an orderwire window, and a number of data windows. The synchronization window is a short loopback switch state and is used by the MCS to synchronize its transmit timing to the on-board switch-state clock. Network control data are transmitted from the MCS to all the earth stations through the reference burst window. The orderwire window is dedicated to the transmission of station status and channel request information, and is also used for acquisition/synchronization error measurements. Station traffic bursts are routed to the proper destination beams through their pre-assigned data windows. This is illustrated in Figure 3-2. The on-board IF switch design allows either point-to-point or point-to-multipoint switch-state operation as desired.

3.2.1 SWITCH-STATE CONNECTION

When a point-to-point switch-state configuration is selected, each input channel is connected to a distinct output channel, and a transmitted burst is routed to only one down-link beam during the assigned time slot. Since the MCS must communicate with all earth stations in the network, four reference burst slots (one for each beam) are reserved as shown in Figure 3-3. (In the figure, the primary MCS is assumed to be located in the Cleveland beam and a backup in the Los Angeles beam.) An orderwire slot in each beam is time-shared by all the earth stations

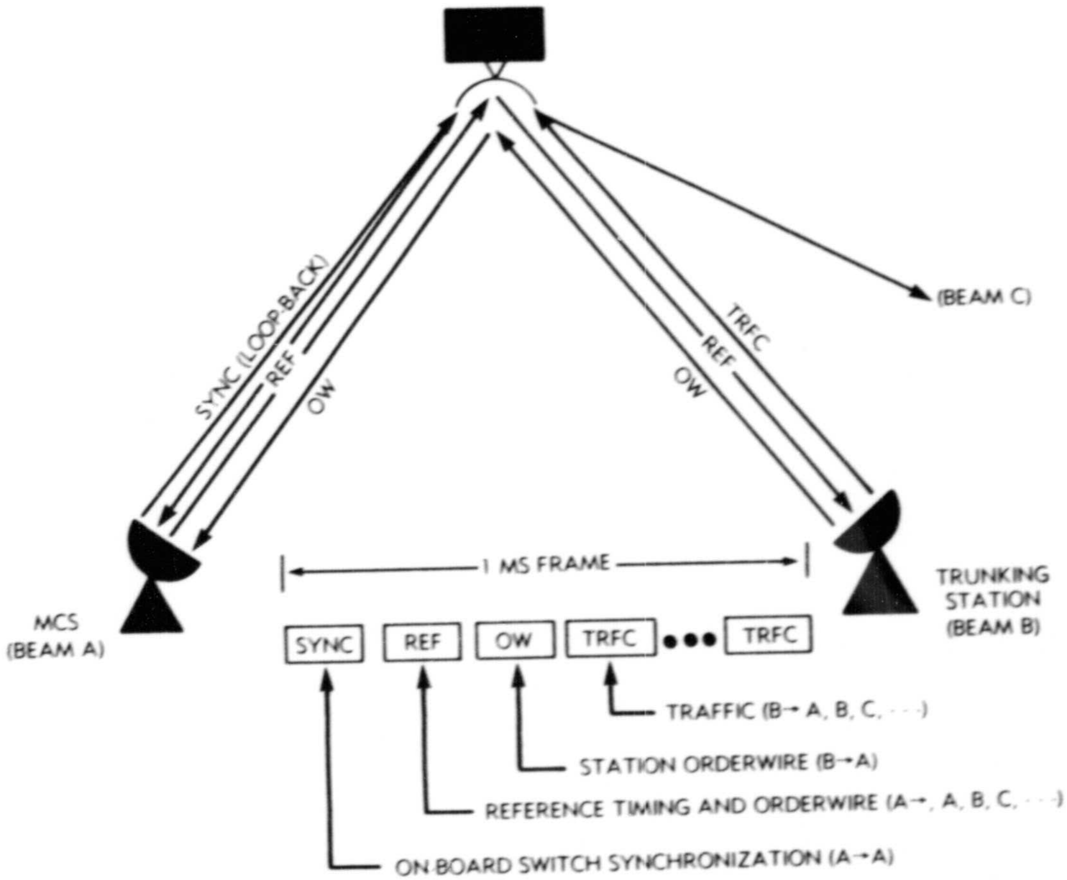
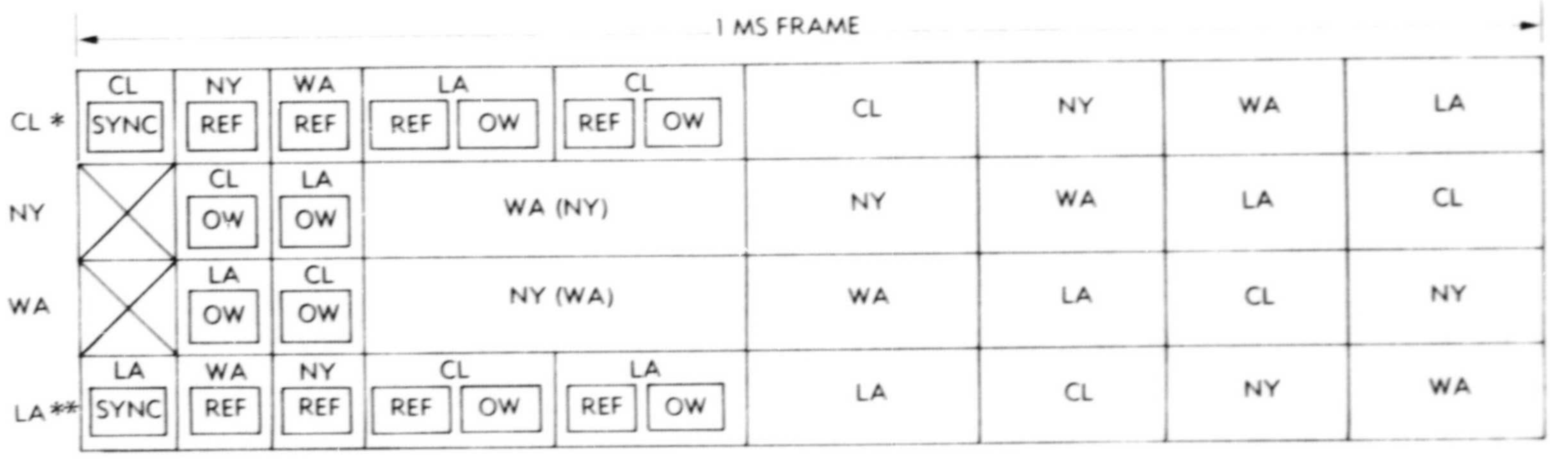


Figure 3-2. Various Trunk Network Bursts



* PRIMARY MCS LOCATION

** BACK-UP MCS LOCATION

Figure 3-3. Switch-State Organization for Point-to-Point IF Switch Connection (CL - Cleveland, NY - New York City WA - Washington, D.C., LA - Los Angeles) in that beam. (Only one time slot is sufficient for the experimental system.) For redundancy, additional time slots are allocated for the secondary reference and orderwire bursts.

The point-to-multipoint switch-state configuration allows bursts to be routed to multiple down-link beams in a broadcast mode to all the beams. Figure 3-4 shows reference and orderwire burst transmissions using broadcast switch states. The advantages of this method are simpler network control, more efficient channel utilization, and reduced earth station complexity. It is particularly suited for video teleconferencing, digital TV broadcasts, and multidestinational data transmission. Figure 3-5 illustrates that the second approach provides more flexible channel assignment over the first one for point-to-multipoint message transmission.

Closed-loop synchronization may also be realized by individual trunking stations via broadcast orderwire slots.

3.2.2 FRAME QUANTIZATION

The 1-ms TDMA frame is divided into 4,000 frame units, and each frame unit consists of 32 QPSK symbols or equivalently a 64-kbit/s traffic channel (Figure 3-6). The synchronization window length is eight frame units (or 2 μs), and data window lengths are integer multiples of one frame unit. Any loopback data window must be at least 16 frame units long (or 4 μs) to distinguish it from the synchronization window. On-board switching occurs on a frame unit boundary, and its position is stored in the switch control memory as a 12-bit number. The finest switch-state quantization is obtained by using a frame unit of one symbol period; this results in 128,000 frame units per frame.

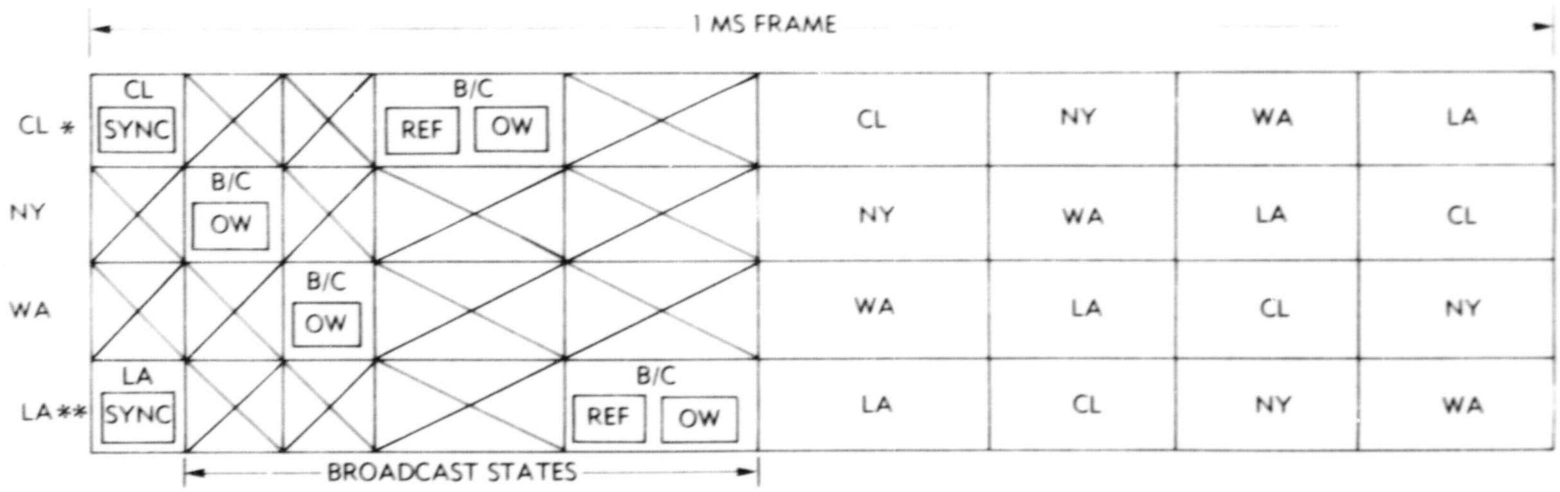


Figure 3-4. Switch-State Organization for Point-to-Multipoint IF Switch Connection

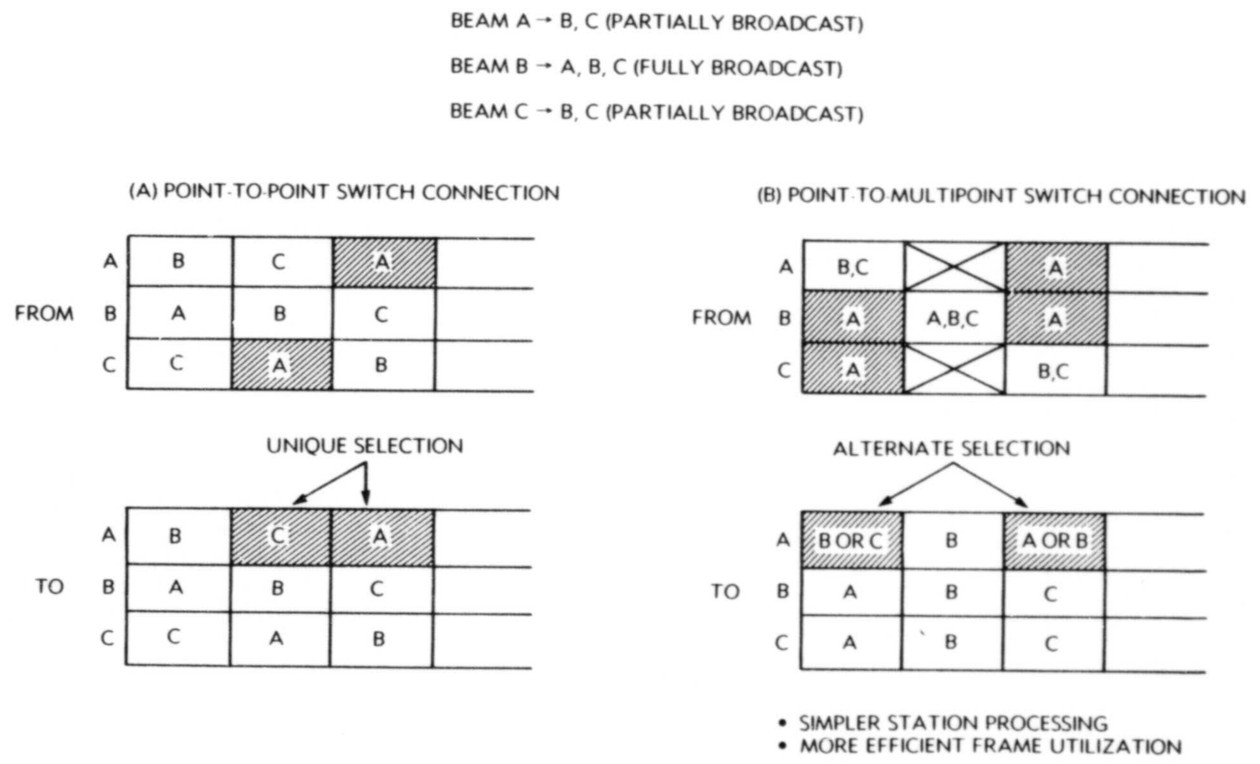


Figure 3-5. Comparison of Two Types of Switch State Connections to Accommodate Point-to-Multipoint Message Transmission

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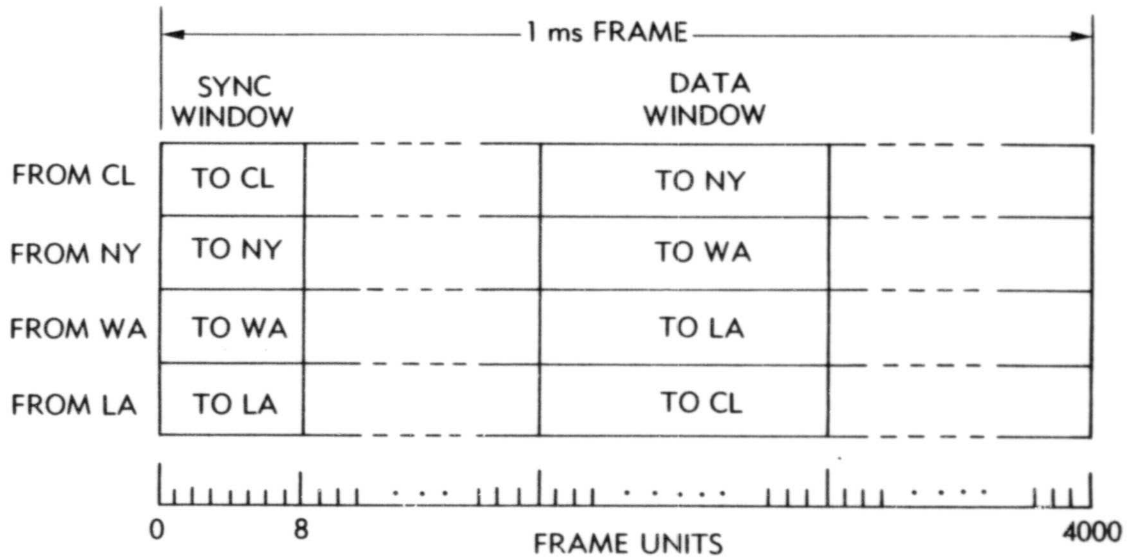

ONE FRAME = 4000 FRAME UNITS

ONE FRAME UNIT = 250 ns

= 32 QPSK SYMBOLS (64 BITS)

= 64 kbit/s TRAFFIC CHANNEL

Figure 3-6. Switch-State Quantization

A 17-bit number is required to represent a switching position. In general, a finer frame quantization would yield a better TDMA frame efficiency due to nearly optimized switch-state scheduling. However, a more complex switch controller would be needed with a higher clock frequency and a larger switch control memory.

3.2.3 CONTROLLER MEMORY SIZE

For an n x n switch matrix with k frame unit quantization, the controller must store n^2 bits of crossbar point states and $\lceil \log_2 k \rceil$ bits of a switch-state duration (or switch transition time), where $\lceil x \rceil$ represents the least integer not less than x. Since a number of switch states necessary for an optimum traffic scheduling is approximately n^2 (see Subsection 3.6), the total storage required for a complete switch-state assignment is

$$n^2 \left(n^2 + \lceil \log_2 k \rceil\right) \text{ bits}$$

For $n \approx 4$ and $k = 4000$, four hundred forty-eight (448) bits of memory are needed. The controller possesses an active switch state memory of 448 bits and equal alternate memory that stores new switch-state assignment data. The third memory is also required as a backup for the two alternate memories. The actual memory size selected may vary depending on the switch-state representation method and FEC coded memory option.

3.3 FRAME AND SUPERFRAME STRUCTURES

The frame and superframe structures described in this subsection can accommodate up to 32 trunking stations per beam and a total of 128 active stations in the network; these structures are easily expandable to a larger number of earth stations.

3.3.1 FRAME STRUCTURE

The trunk TDMA frame structure shown in Figure 3-7 contains four types of bursts, each of which starts with a carrier and bit-timing recovery (CBTR) sequence followed by a unique word (UW), where the CBTR pattern is common to all bursts. Burst types are identified by four distinct UW patterns, as in the INTELSAT V TDMA system [1],[2]. Alternately, two additional bits can be inserted into the bursts for identification as in the SBS system [3].

The synchronization burst (referred to as sync burst) is used by the MCS to synchronize its transmit clock to the on-board switch-state clock and to regenerate on-board timing on the ground. The metering segment of the burst has a fixed bit sequence, and on-board switch-state timing is detected by intersecting a portion of the metering segment with the synchronization window trailing edge. This burst is also used to measure on-board clock drift to compute clock correction values.

The reference burst transports orderwire data to trunking stations for network control. The UW detection pulse of a reference burst also identifies a start of receive frame which, along with a burst time plan (BTP) and transmit timing control

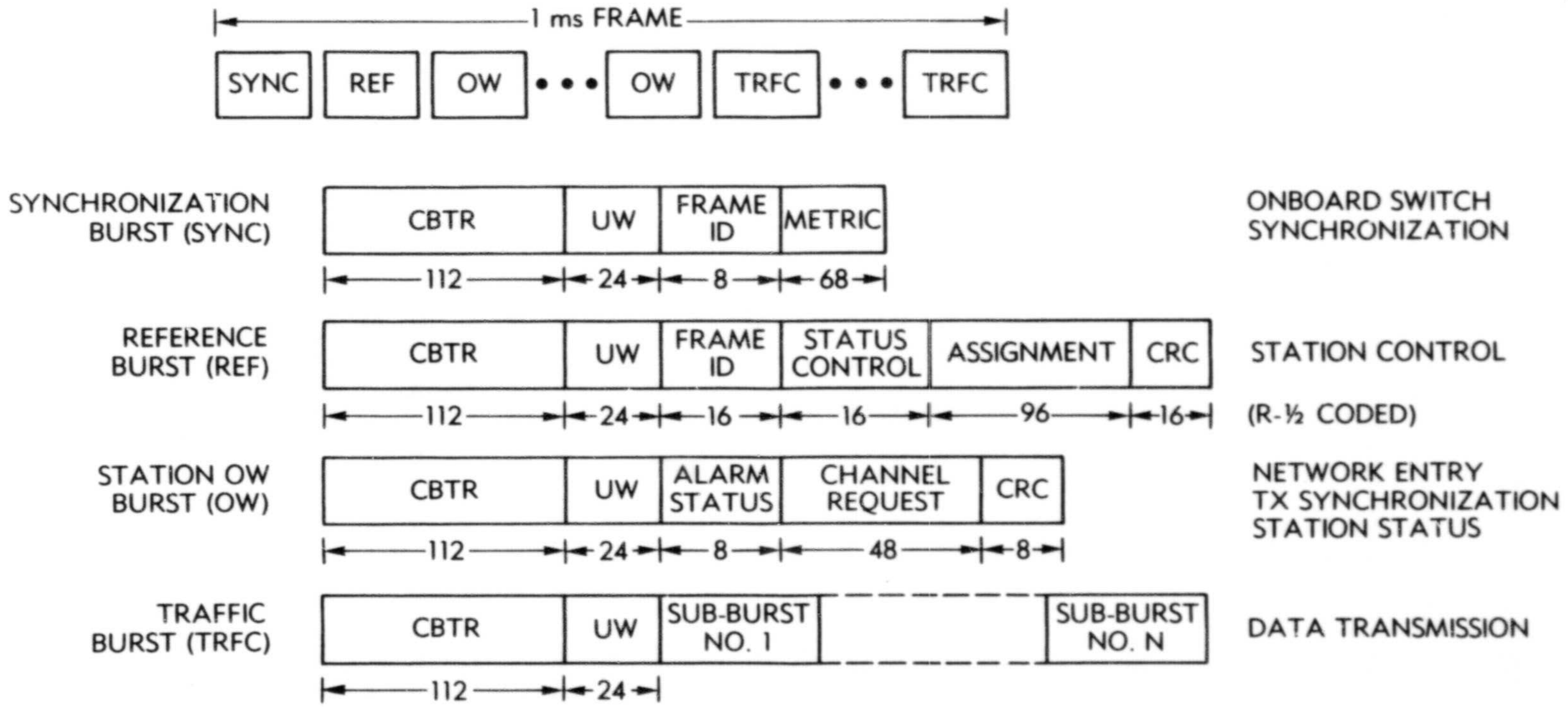

Figure 3-7. Trunk Network Frame Structure

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data, generates transmit and receive timing for other bursts at a trunking station.

The orderwire field of the reference burst consists of frame identification, status and control, channel assignment, and cyclic redundancy check (CRC) bits. These are FEC coded using, for instance, a (16, 8) shortened residue code. The frame ID field is 16 symbols (32 bits) long with 8 symbols of actual data and the other 8 symbols for FEC parity bits. Network control timing is generated from the frame ID number. The status and same number of parity bits. The S/C data for each trunking station are time-multiplexed over eight consecutive frames (i.e., 128 information bits), and four duplicated copies are transmitted during one control frame (1,024 frames) for enhanced error protection.

The channel assignment field is used to transmit a BTP to trunking stations, which in turn create new receive and transmit timing data. The new channel assignment is executed by an MCS command at the superframe (65,536 frames) boundary. Thus, the proposed scheme can easily incorporate demand-assignment operation. The reference burst orderwire is encoded using a 16-bit error-detecting CRC code. The synchronization bursts, station orderwire bursts, and traffic bursts are not FEC encoded since bit errors in these bursts are not critical for network control.

A station orderwire burst is a communications channel from a trunking station to the MCS that is used for engineering service data transmission, such as alarm and status data and channel requests. The same burst is also used for transmit timing error and burst power measurements at the MCS. No orderwire data are transmitted in traffic bursts. The dedicated orderwire burst approach has a number of advantages over a more traditional method that uses a portion of a traffic burst preamble to send orderwire data. Some of the advantages are:

a. A trunking station can perform network acquisition at any time, and there is no need to share a traffic burst slot for acquisition and data transmission.

b. Orderwire data are directly routed to the MCS without assisting stations.

c. A centralized monitoring system is easily implemented at the MCS, i.e., synchronization error, burst power level, and bit error rate can be measured at the MCS.

However, extra time slots are required for orderwire bursts to implement the present approach and the resulting frame overhead is quite small. In the experimental system, only one orderwire slot is needed in each beam.

The traffic burst consists of a number of sub-bursts, and each sub-burst is destined to one (or more for a multipoint connection) trunking station.

3.3.2 SUPERFRAME STRUCTURE

A superframe structure allows a means of controlling network operation in groups of frames. Figure 3-8 shows a trunk network superframe. A multiframe consists of 32 frames, and 32 multiframes form a control frame. Each multiframe is assigned to one trunking station for orderwire transmission and status/control data reception. Thus, a maximum of 32 stations in the same beam share an orderwire slot for engineering service communication. Station orderwire bursts are also used for timing

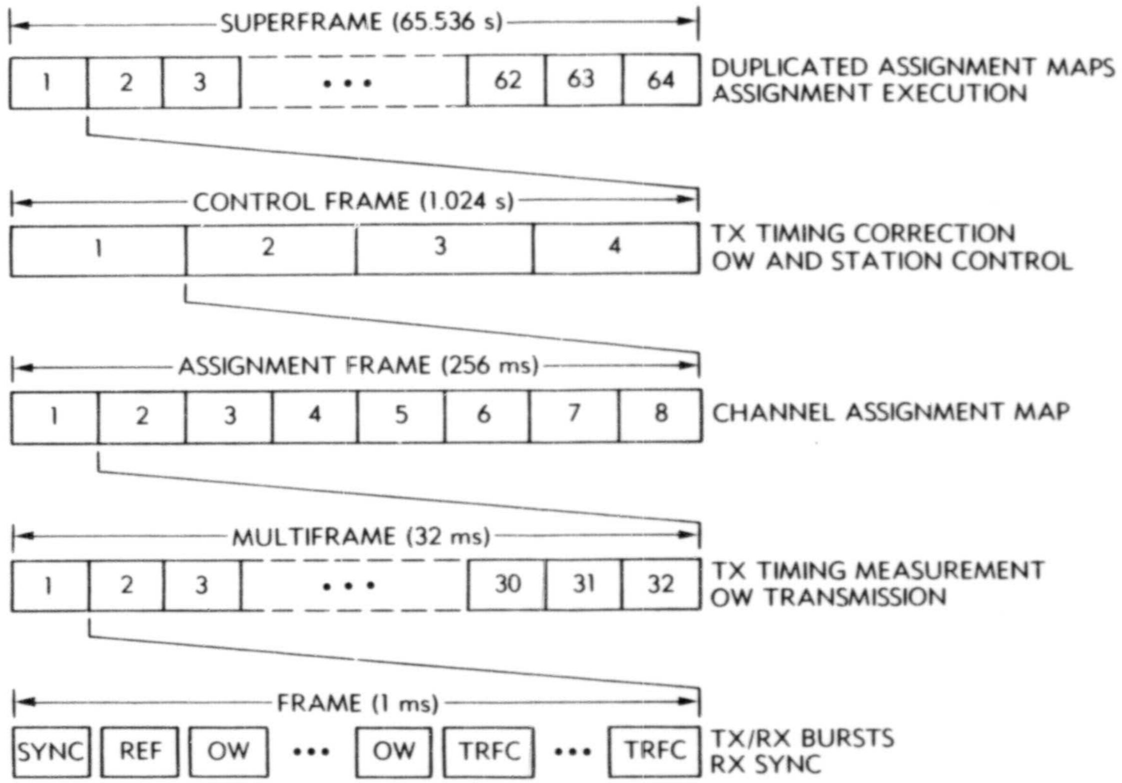

Figure 3-8. Trunk Network Superframe Structure

error measurements at the MCS for feedback synchronization. With a broadcast orderwire window, loopback synchronization is also possible by each station.

Transmit and receive BTP data require four multiframes each, and a complete channel assignment is transmitted in one assignment frame or eight multiframes. Two hundred and fifty-six (256) duplicated copies are transmitted during one superframe. The channel assignment map can be updated once every 66 seconds.

3.3.3 ERROR PROBABILITY OF ORDERWIRE DATA

The reference burst orderwire is triply error protected by FEC and CRC coding, and multiple-copy transmission. A (16, 8) shortened quadratic residue code is used for random double-error correction, and uncorrectable error patterns are detected by a 16-bit CRC code. The generator polynomial of the quadratic residue code is given by

$$g(x) = x^8 + x^5 + x^4 + x^3 + 1.$$

Table 3-1 lists the error probability of reference burst orderwire data at channel bit error rates of 10^{-2} and 10^{-3}. According to the table, the network operates reliably at the channel bit error rate of 10^{-2}.

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Table 3-1. Error Probability of Reference Burst Orderwire Data

Channel BER	Decoder Output BER	Frame ID Error Probability	S/C Field Error Probability	Assignment Error Probability
10^{-2}	1.12×10^{-4}	1.6×10^{-2}	2.1×10^{-4}	1.4×10^{-19}
10^{-3}	1.12×10^{-7}	1.6×10^{-5}	2.8×10^{-16}	$<10^{-100}$

3.3.4 SWITCH-STATE ASSIGNMENT CHANGE

The switch-over from the present channel assignment to a new assignment must be executed without any interruption on the earth station traffic, and a coordinated switch-over procedure must be exercised between the on-board IF switch and trunking stations. To achieve this goal, a blink switch state is established on the satellite. The on-board switch controller has a superframe counter which generates a pulse once every superframe. This pulse triggers the controller to eliminate the synchronization window for one frame. The MCS detects this state as a loss of a synchronization burst and locks its superframe timing to the blink switch states. The superframe acquisition process may require several superframe periods. The assignment execution command is sent to the satellite via the TT&C link, and the execution occurs at the following blink state. This is illustrated in Figure 3-9. Trunking stations receive an assignment change command via the reference burst orderwire.

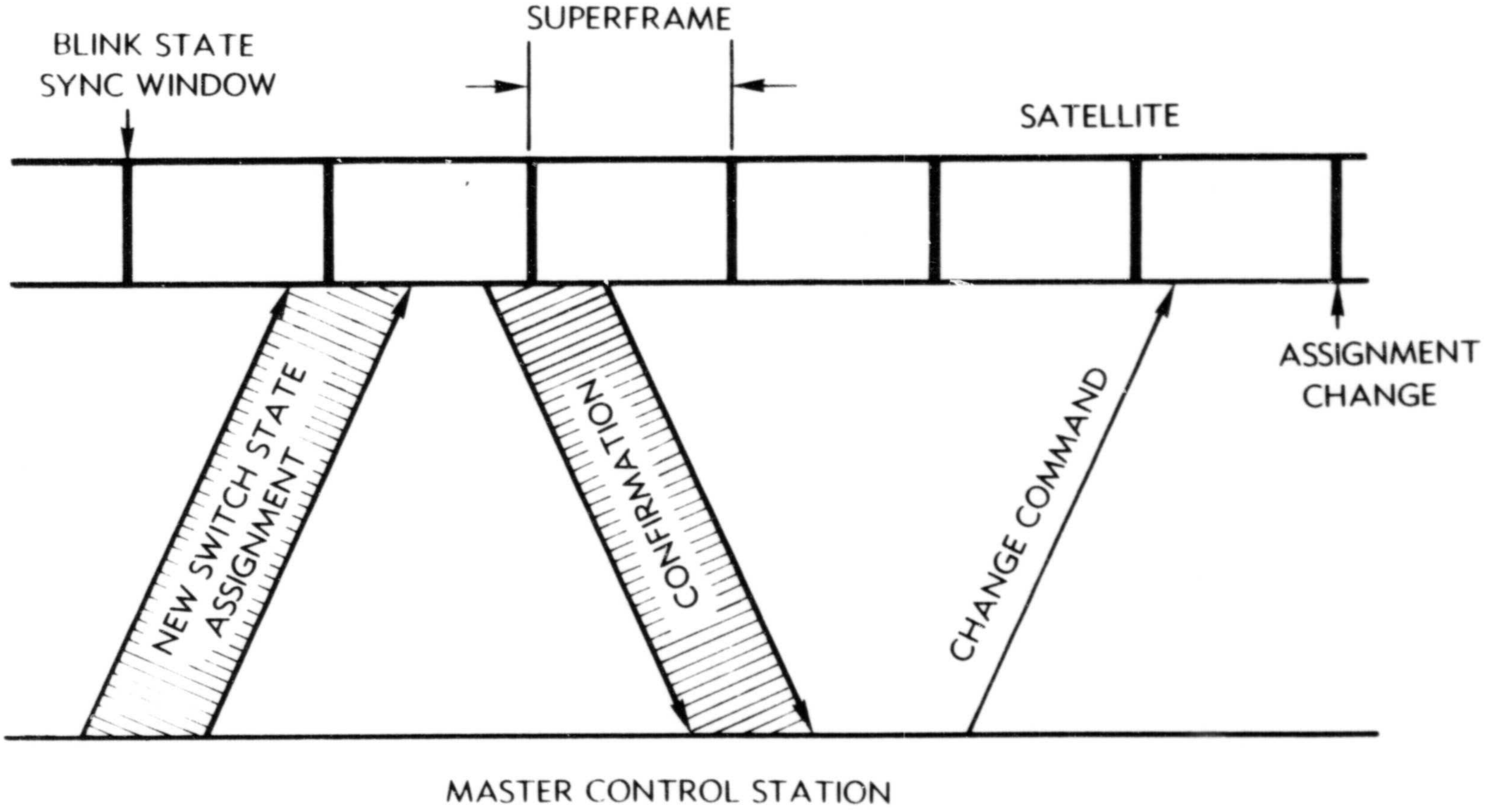

Figure 3-9. Channel Assignment Execution

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3.4 ACQUISITION AND SYNCHRONIZATION

3.4.1 NETWORK START-UP PROCEDURE

A network start-up procedure is illustrated in Figure 3-10. Initially, there is no timing relationship between the on-board clock and ground station clock, and the MCS transmits an FSK acquisition signal to search the synchronization window. The acquisition signal is looped back by the window and detected at the MCS. The transmit timing is then adjusted so that the frequency transition of the FSK signal occurs at about the center of the synchronization window. Fine synchronization is achieved by transmitting synchronization bursts.

After clock synchronization has been established between the satellite and MCS, reference bursts are transmitted to all beams through the reference burst time slot. A trunking station detects the reference burst UW and synchronizes its receive timing to the detected UW pulses. Initial acquisition data are extracted from the decoded orderwire data, and the trunking station begins initial acquisition by transmitting orderwire bursts to the preassigned orderwire slot. The MCS detects these bursts, measures the timing error, and sends back transmit timing correction data to the trunking station for fine synchronization. When the timing error becomes no more than ±4 symbols, the trunking station is in the steady-state synchronization mode and can transmit traffic bursts in accordance with the burst time plan.

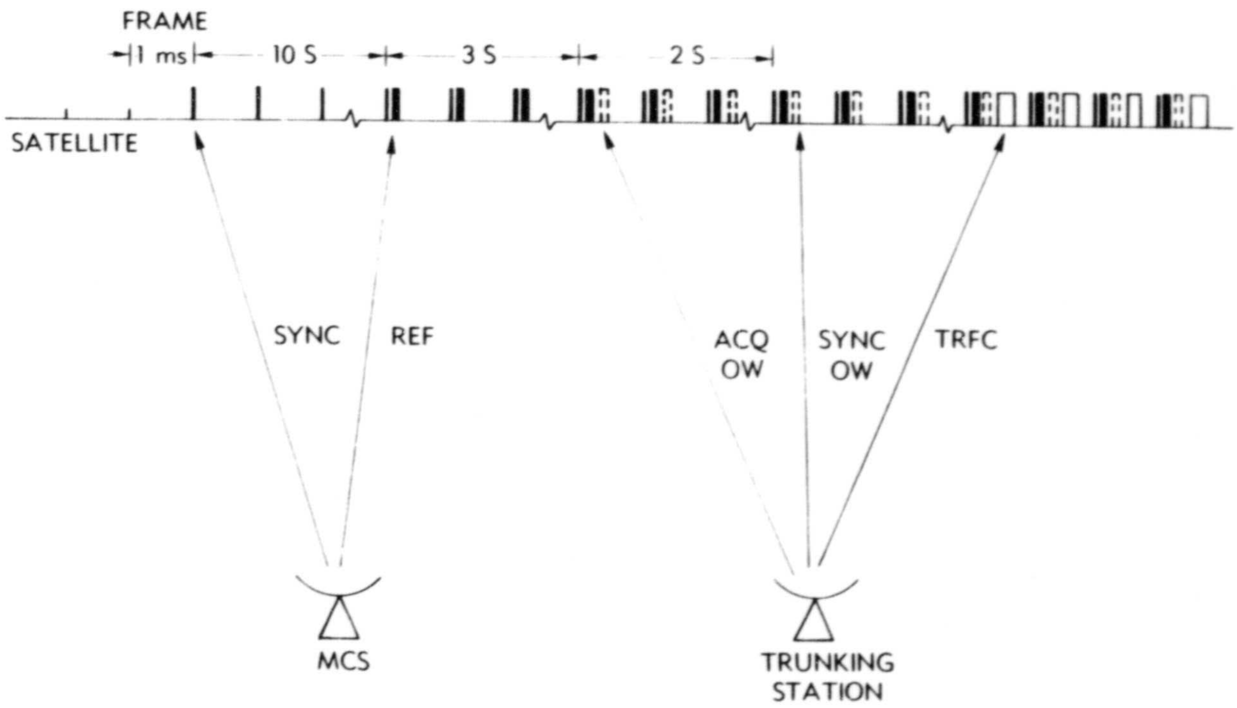

Figure 3-10. Network Start-Up Procedure

3.4.2 MCS ACQUISITION

Among various SS-TDMA acquisition and synchronization techniques [4]-[7], the FSK acquisition method is described in this section. The acquisition signal is a periodic frequency-shift keying (FSK) signal with frequencies f_1 and f_2 and a repetition period of 1 ms (Figure 3-11). The FSK acquisition signal power is 20 dB below the normal TDMA signal to avoid interference with the on-going TDMA burst transmission. Low-power acquisition is not necessary in the experimental system since only one control station exists in the entire network and the network is not required to be operative under an MCS outage condition. However, an operational system must be protected from a single control station failure by providing backup control stations. During normal operation, one control station performs network control functions, and others may be in the initial acquisition process. No traffic interference should result under this condition. Low-power acquisition could be effectively employed to achieve this goal and implemented in the experimental system for testing purposes.

The MCS continuously transmits the acquisition signal to locate the synchronization window as shown in Figure 3-12. At the receiver, the signal is discriminated by two narrowband filters and envelope detected, and the pulse widths of f_1 and f_2 signals are measured using a 5-MHz clock. The measurement is repeated and integrated over a number of frames (typically 64) to reduce the false detection probability. The transmit timing correction is performed as follows.

Let T_1 and T_2 be respectively the measured pulse widths of the f_1 and f_2 detectors gated with a 4-μs aperture. Depending on the values of T_1 and T_2, the following decision is made:

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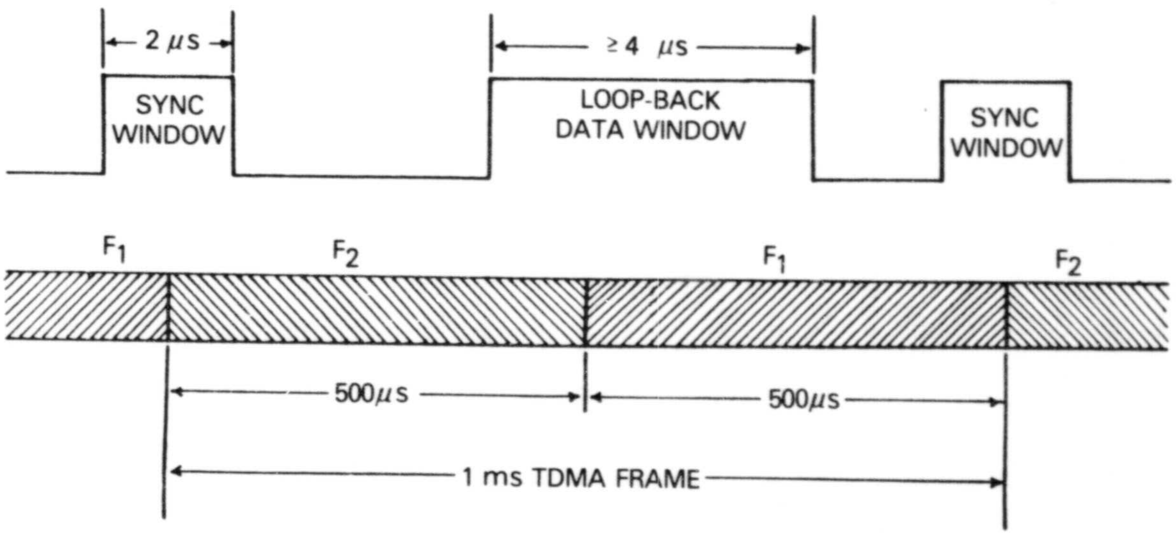

Figure 3-11. Low-Power FSK Acquisition of Synchronization Window

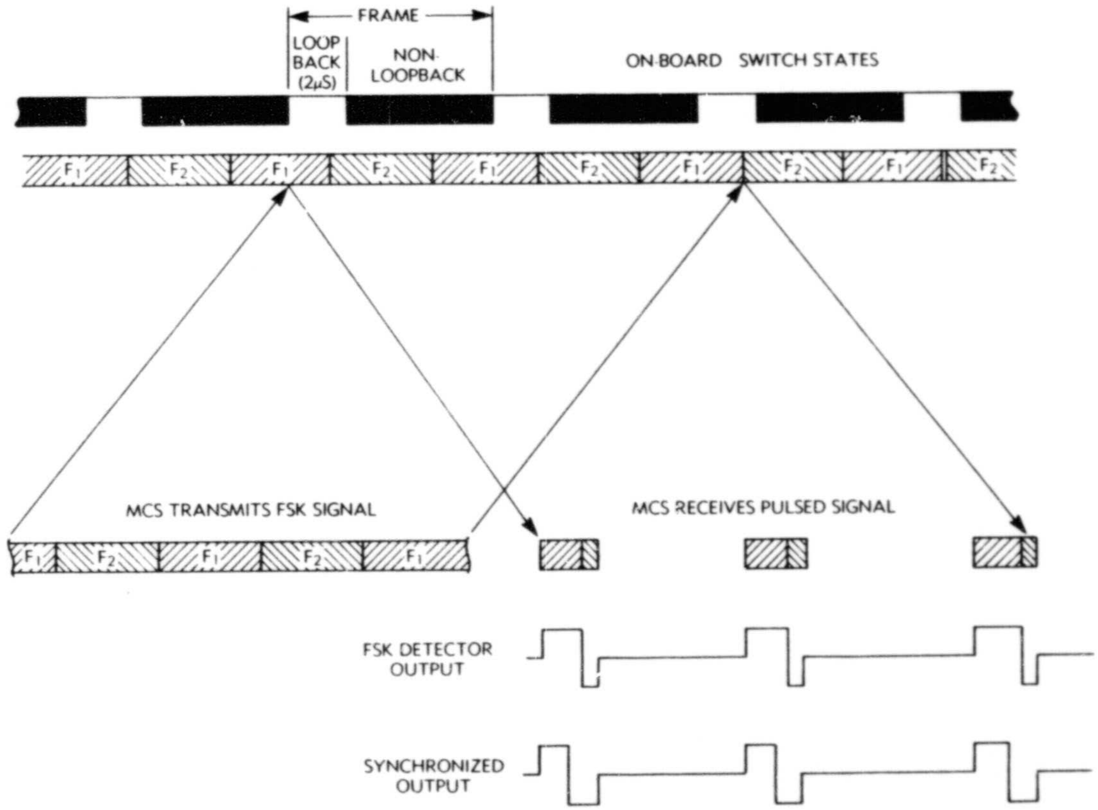

Figure 3-12. On-board Timing Detection by an FSK Acquisition Signal

$T_1 + T_2 > 2.4\ \mu s$: Loopback data window is detected

$1.6\ \mu s \leq T_1 + T_2 \leq 2.4\ \mu s$: Synchronization window is detected

$T_1 + T_2 < 1.6\ \mu s$: The pulse is caused by noise

If the synchronization window is not detected, the search will continue. When the synchronization window is detected, an optimal binary search procedure locates a frequency transition of the FSK signal at the center of the window.

The optimal binary search procedure is initiated when the condition $1.6\ \mu s \leq T_1 + T_2 \leq 2.4\ \mu s$ is met. If only f_1 (or f_2) signal is detected, i.e., $T_2 = 0$ (or $T_1 = 0$), delay (or advance) the transmit clock by 500 µs and wait for one round-trip propagation time. Then, measure the pulse widths: if only f_1 (or f_2) signal is detected, i.e., $T_1 = 0$ (or $T_2 = 0$), advance (or delay) the transmit clock by 250 µs. When this process is repeated, the timing uncertainty will successively be reduced to 125 µs, 63 µs, 32 µs, and so on, eventually leading to the detection of two frequencies in the synchronization window. The initial acquisition procedure terminates when condition $T_1 \approx T_2$ ($|T_1 - T_2| < 400$ ns) is achieved.

3.4.3 MCS SYNCHRONIZATION

Upon completion of the initial acquisition process, sync bursts are transmitted to the synchronization window at the normal TDMA burst power level. The initial transmit timing is adjusted so that the center of the metering segment intersects with the synchronization window trailing edge. This is shown in Figure 3-13. The received metering sequence data are integrated

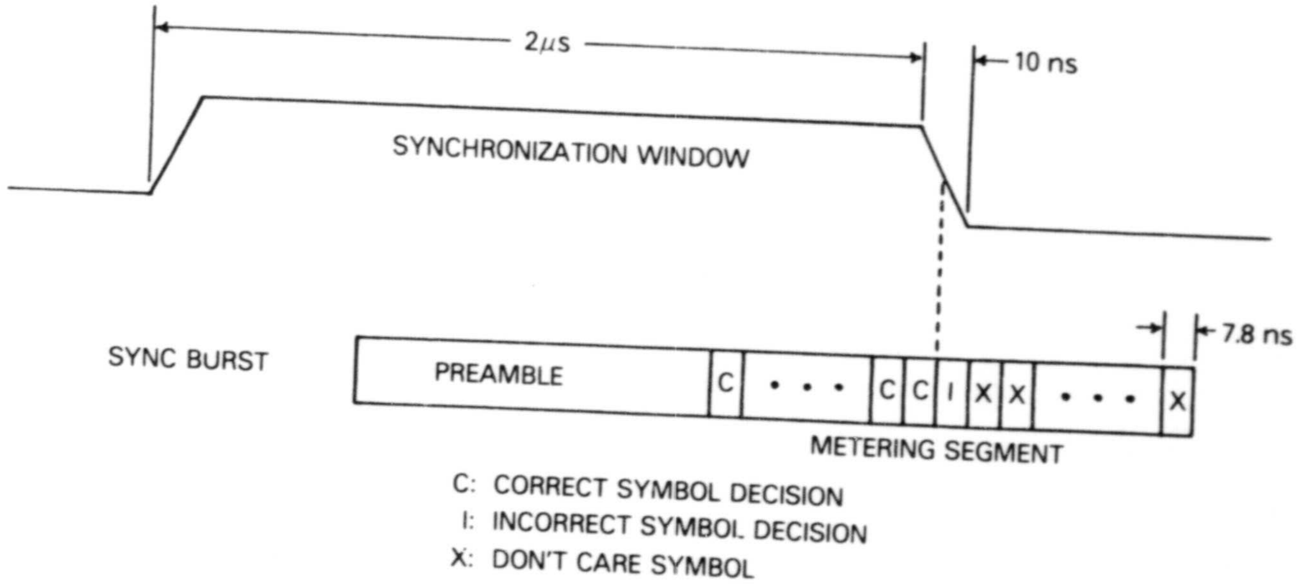

Figure 3-13. On-Board Switch-State Synchronization by Synchronization Bursts

over 64 frames, and the trailing edge intersection is determined by setting a proper error threshold. The sync bursts are subsequently shifted to the left so that only the last 16 symbols of the metering segment are truncated by the window. The acquisition process terminates and enters steady-state synchronization when the transmit timing error becomes no more than two symbols.

3.4.4 TRUNKING STATION ACQUISITION AND SYNCHRONIZATION

An open-loop acquisition method is considered for the trunking station to synchronize its transmit clock [8]-[11]. The spacecraft position is determined by three ranging stations (triangulation method) or spacecraft orbit ephemeris based on TT&C data. The range from each trunking station is calculated from the spacecraft position and the geographic location of the station, and translated into the time delay, T_d, of the transmit burst start time relative to the receive reference frame marker. Figure 3-14 shows the initial acquisition procedure. The time delay is given by

$$
\begin{aligned}
T_d &= T_a - T_x \quad \text{if} \quad T_a \geq T_x \\
&= T_f - T_x + T_a \quad \text{if} \quad T_a < T_x
\end{aligned}
$$

where

$T_x = \frac{2d}{c} - T_f \left[\frac{2d}{cT_f}\right]$ = frame timing adjustment for propagation delay

$[x]$ = largest integer not greater than x

d = satellite range

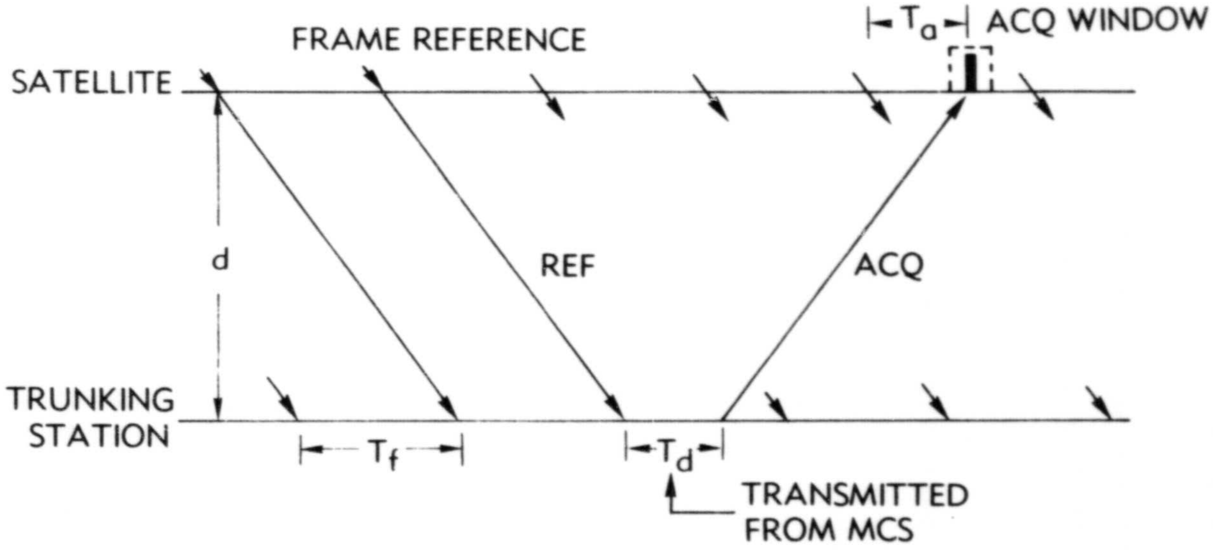

Figure 3-14. Open-Loop Acquisition Based on Satellite Range Calculation

c = speed of light

T_f = frame period (1-ms)

T_a = center of the acquisition window measured from the start of receive frame.

The acquisition and synchronization procedure at the trunking station follows a sequence of burst timing control steps:

a. receive synchronization,
b. transmit acquisition based on the above method, and
c. transmit synchronization.

These are described in the following subsections.

3.4.4.1 Receive Synchronization

A trunking station opens a wide aperture to detect a reference burst UW. When a UW pulse is detected, the receive symbol counter is set to 1 ms, with the reception of another UW pulse expected one frame later; at the same time, the aperture width is reduced to several symbols. When four consecutive reference bursts are detected, the trunking station is in the receive synchronization mode and initiates superframe synchronization. Otherwise, the reference burst search process continues with a wide aperture. Superframe synchronization is accomplished by decoding successive frame ID numbers in the reference burst orderwire. During this process, the transmit time delay number, T_d, and channel assignment data are also decoded.

3.4.4.2 Transmit Acquisition

Each trunking station is assigned 32 consecutive time slots in a control frame for orderwire burst transmission. These orderwire frames are easily identified from the receive frame number and the nominal satellite range of the trunking station, since the maximum propagation delay variation, 140 μs, due to the satellite position shift does not exceed half of the frame period. The transmit symbol counter is delayed by T_d from the receive counter content, and an orderwire burst is transmitted in the first orderwire frame as determined above.

The acquisition window length is 1.333 μs for a satellite range measurement accuracy of ±200 meters and is included in the station orderwire time slot length of 2.9 μs. The acquisition timing error is measured at the MCS as shown in Figure 3-15 and sent back to the trunking station, which in turn corrects its transmit timing in the following orderwire burst transmission. The acquisition process terminates and enters a synchronization process when the timing error is reduced to no more than four symbols.

3.4.4.3 Transmit Synchronization

When an MCS message on the synchronization state is detected, the trunking station is allowed to transmit traffic bursts carrying terrestrial channels. Transmit synchronization, as in the acquisition mode, is controlled according to the timing error measurements at the MCS. The error control data are sent to the trunking station via the reference burst orderwire, and

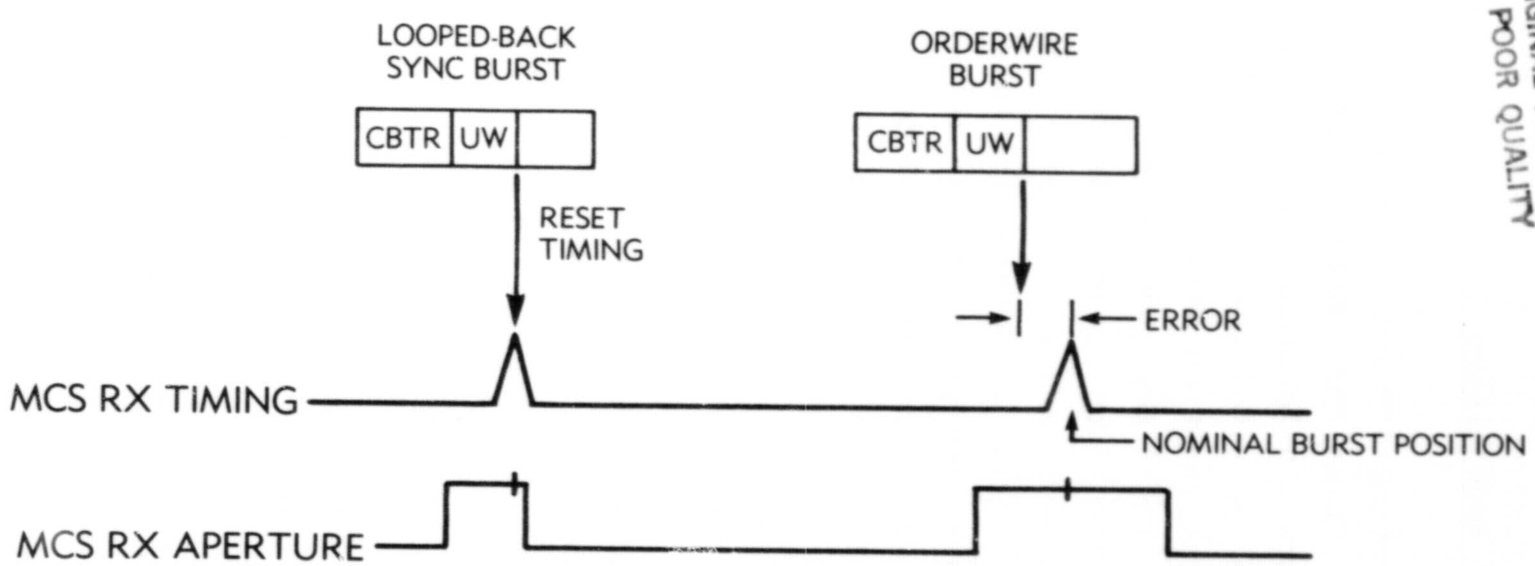

Figure 3-15. Transmit Timing Error Measurements at the MCS

the incremental error value (e) is subsequently adjusted in the next orderwire transmission as shown in Figure 3-16.

3.4.5 SYNCHRONIZATION PARAMETERS

Table 3-2 summarizes typical synchronization parameters for the trunk network. It should be noted that a relatively larger guard time is allocated for traffic bursts than would be required to allow uninterrupted service during several seconds of MCS reference burst outage.

Table 3-2. Summary of Trunk Network Synchronization Parameters

	Acquisition Accuracy	Synchronization Accuracy	Guard Time
Sync Burst	±200 ns (±26 symbols)	±16 ns (±2 symbols)	N/A
Reference Burst	N/A	±16 ns (±2 symbols)	N/A
Orderwire Burst	±667 ns (±85 symbols)	±32 ns (±4 symbols)	1.333 μs (171 symbols)
Traffic Burst	N/A	±32 ns (±4 symbols)	125 ns (16 symbols)

3.5 ORDERWIRE TRANSMISSION

Trunk network control requires an orderwire channel for the exchange of the control and status information required for acquisition and synchronization, channel assignment, adaptive

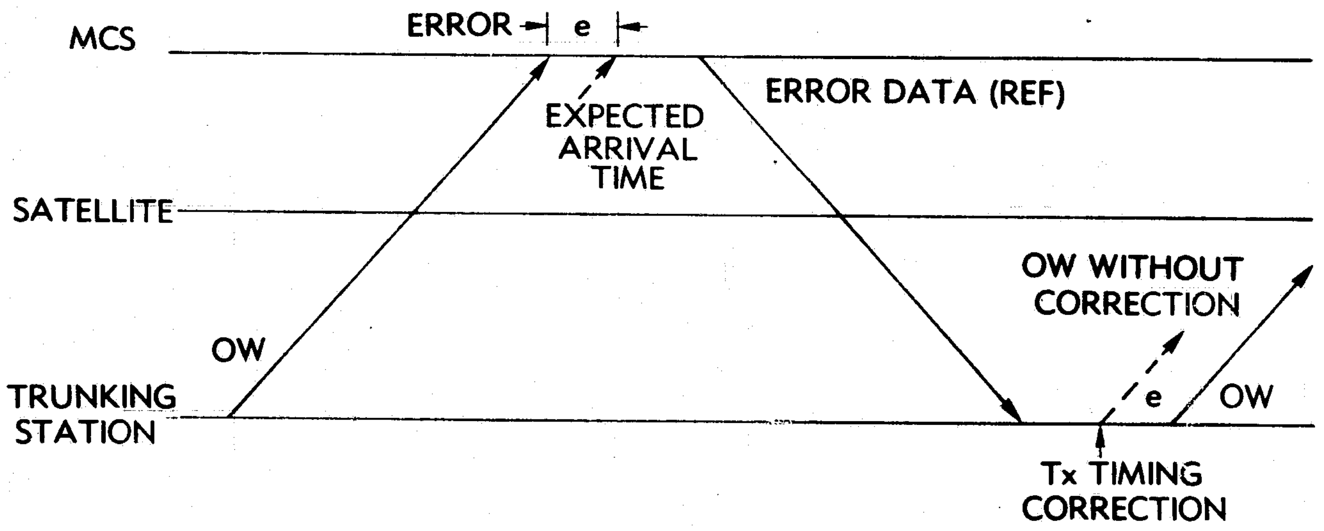

Figure 3-16. Feedback Control Synchronization

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power control, and terminal status monitoring. A satellite system operating in a global beam (all users in one down-link beam) generally accommodates this requirement by apportioning a certain number of bits in each traffic burst for orderwire information. In an SS-TDMA network employing spot beams, this approach is not feasible since traffic bursts are not necessarily routed to the MCS down-link beam.

It is inefficient to provide switching of all traffic to the MCS beam. Instead, distinct orderwire bursts are employed. In addition to synchronization, reference, and traffic bursts, each frame contains several slots for orderwire bursts. During these burst slots, on-board switch connectivity to the MCS is provided. These orderwire slots are shared, over a series of frames, by the terminals in the beam. MCS-to-user orderwire information is contained in the reference burst occurring at the beginning of the frame originating in the MCS beam. The structure of these bursts is shown in Figure 3-17. Sharing of the orderwire slots occurs in a round-robin fashion over a series of 1024 frames (one control frame). Return transmissions from the MCS occur similarly, but staggered in 512 frames as shown in Figure 3-18. The net response time is thus 512 ms plus a round-trip earth-to-satellite propagation delay for a total of approximately 0.762 s (assuming a round-trip delay time of 250 ms).

The concept of time-sharing orderwire data transmission is used in the INTELSAT and SBS systems [1],[3], where the latter system also allocates dedicated time slots for orderwire bursts as described above. Various orderwire messages are also shown in Figure 3-18.

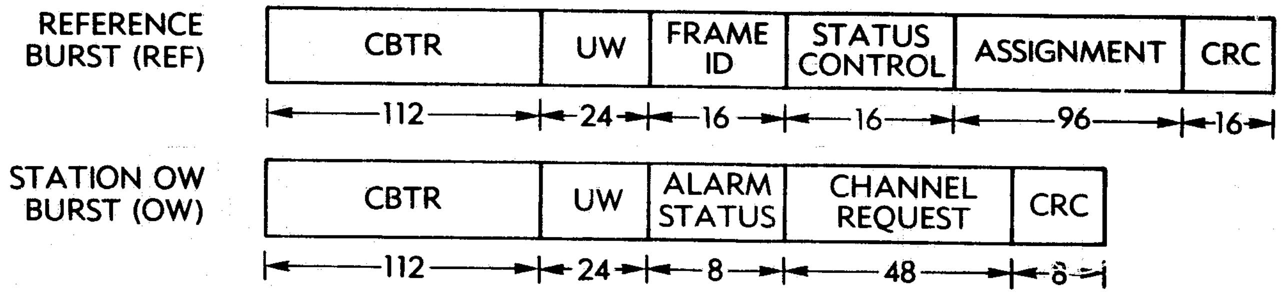

Figure 3-17. Reference and Station Orderwire Burst Formats

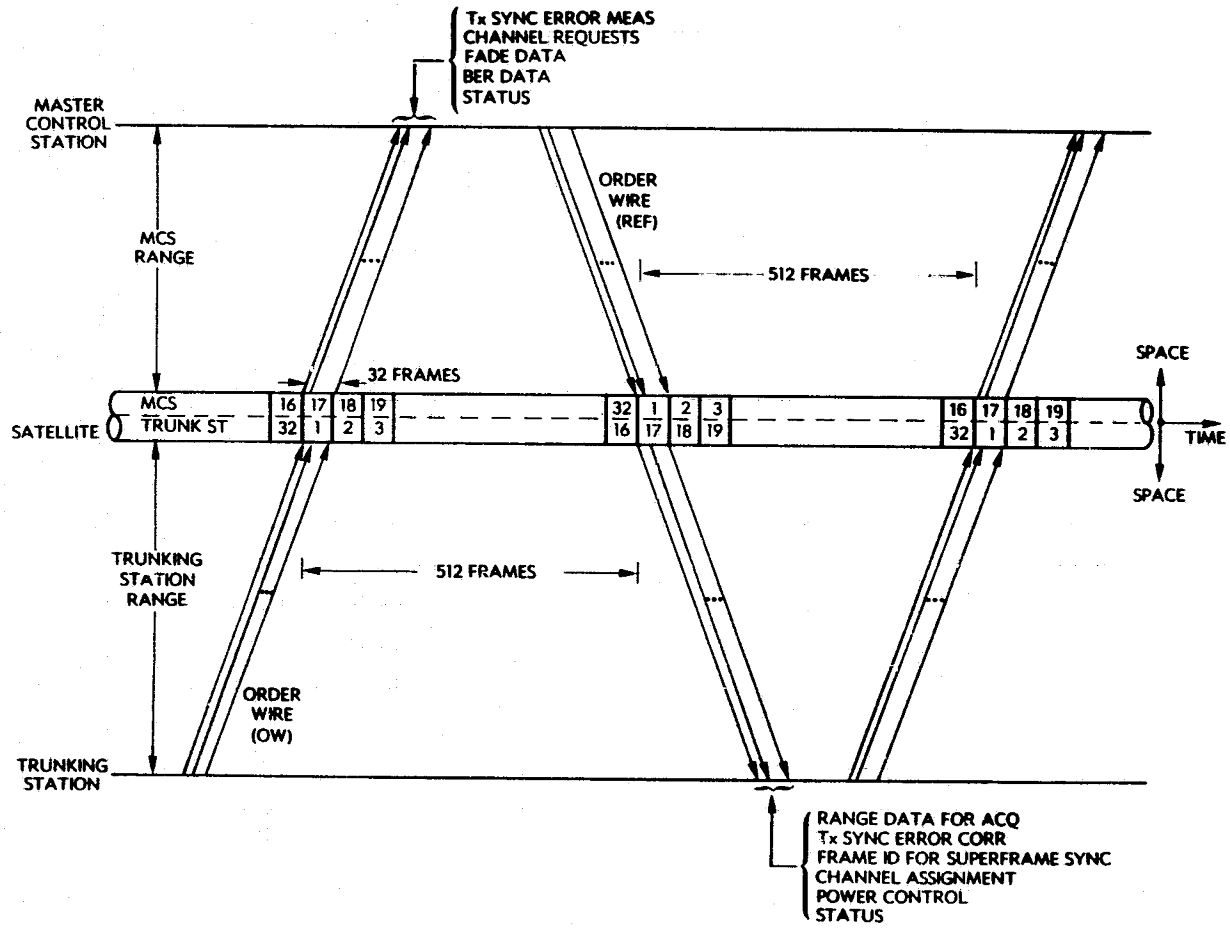

Figure 3-18. Orderwire Transmission Format

3.6 CHANNEL ASSIGNMENT

3.6.1 CHANNEL ASSIGNMENT PROCEDURE

Network traffic is tabulated in the station traffic matrix, shown in Figure 3-19, which indicates the network connectivity and amounts of traffic among network stations. This matrix is then condensed to the beam traffic matrix (Figure 3-20), which identifies the connectivity and traffic volume among various beams. The purpose of channel assignment is to efficiently allocate the beam traffic into a number of switch states so that all the traffic channels are routed to the designated beams with minimum overhead. A combinatorial optimization procedure can be used to perform an efficient channel allocation with desired switch connections. The result of an optimal assignment is shown in Figure 3-21.

The subsequent burst scheduling process allocates a burst preamble to each traffic burst and includes the quantization adjustments of switch-state lengths. Additional switch states are also allocated for the synchronization burst, reference burst, and orderwire burst slots. The frame efficiency resulting from these overheads is better than 95 percent, and a beam traffic capacity of at least 157 T1-channels can be accommodated in the experimental system.

The channel assignment procedure for an SS-TDMA system is summarized in Figure 3-22.

TX BEAM	RX BEAM	CL			NY			WA			LA		
	STATION	CL_1	CL_2	CL_3	NY_1	NY_2	NY_3	WA_1	WA_2	WA_3	LA_1	LA_2	LA_3
CL	CL_1		4			5			1				4
	CL_2	4		3				5		8	6		
	CL_3		3								10		
NY	NY_1	6		12		3			20				2
	NY_2	5			2		10	6				3	
	NY_3		7	5		10				10	1		
WA	WA_1	24	5			6			8		7		
	WA_2	1						8					11
	WA_3		8				2	1			8		
LA	LA_1		6	10	5		1	7		8		5	8
	LA_2		8			3			2		5		4
	LA_3	4			2		5		11		8	3	

Figure 3-19. Station Traffic Matrix

TX \ RX	CL	NY	WA	LA
CL	14	5	14	20
NY	35	25	36	6
WA	38	8	17	26
LA	28	16	28	33

Figure 3-20. Beam Traffic Matrix

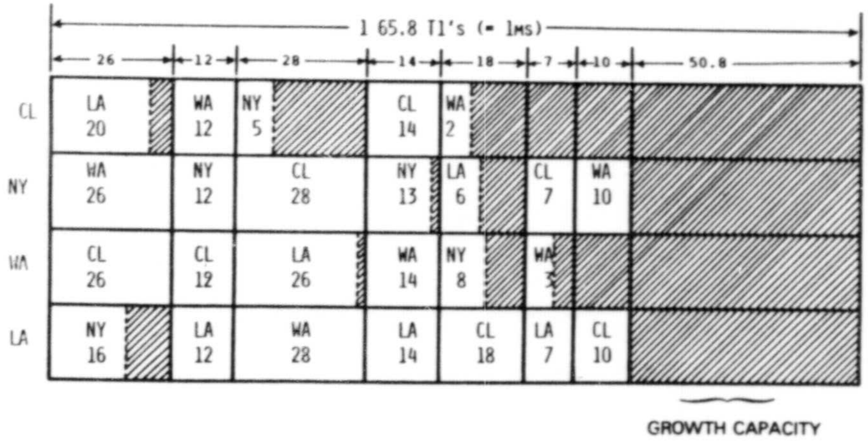

Figure 3-21. Switch-State Assignment

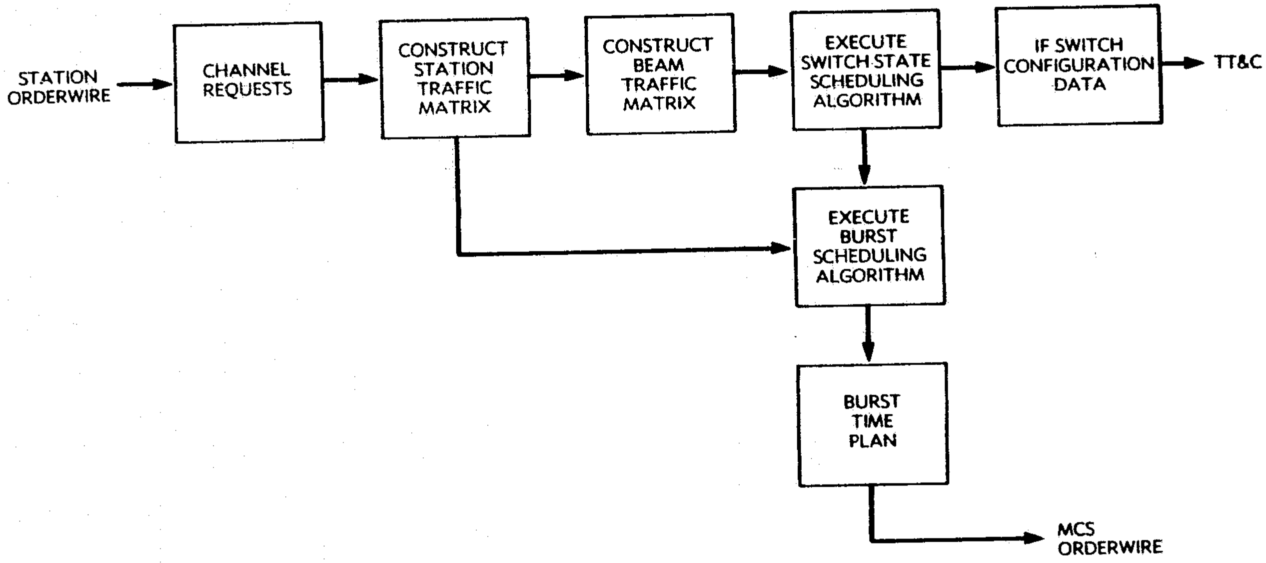

Figure 3-22. Channel Assignment Procedure for an SS-TDMA System

3.6.2 CHANNEL ASSIGNMENT ALGORITHM

Channel assignment problems for various SS-TDMA system configurations have been studied extensively in the past [12]-[17], and a basic algorithm for an n x n switch matrix is presented in the following.

Let C and C' denote the maximum traffic from/to any beam and the capacity requirement resulting from a particular channel asssignment. In general, C' is always greater than or equal to C, and the assignment is optimum when C' equals C. The algorithm described in the following yields an optimum channel assignment for any traffic matrix [14].

Step 1. Express a traffic matrix as the sum of a switch matrix and a new traffic matrix, where the switch matrix has at most one non-zero element in each column and each row, and every row sum and column sum that are maximum in the original matrix remain maximum in the new traffic matrix. This is equivalent to finding a system of distinct representatives from the column sets of the original matrix, and an efficient algorithm exists to accomplish this task.

Step 2. Repeat the above process for the new traffic matrix until a zero traffic matrix results. An example of traffic matrix decomposition is shown in Figure 3-23.

Step 3. The original traffic matrix is the sum of the switch matrices generated in the decomposition process, and each switch matrix defines an on-board IF switch state.

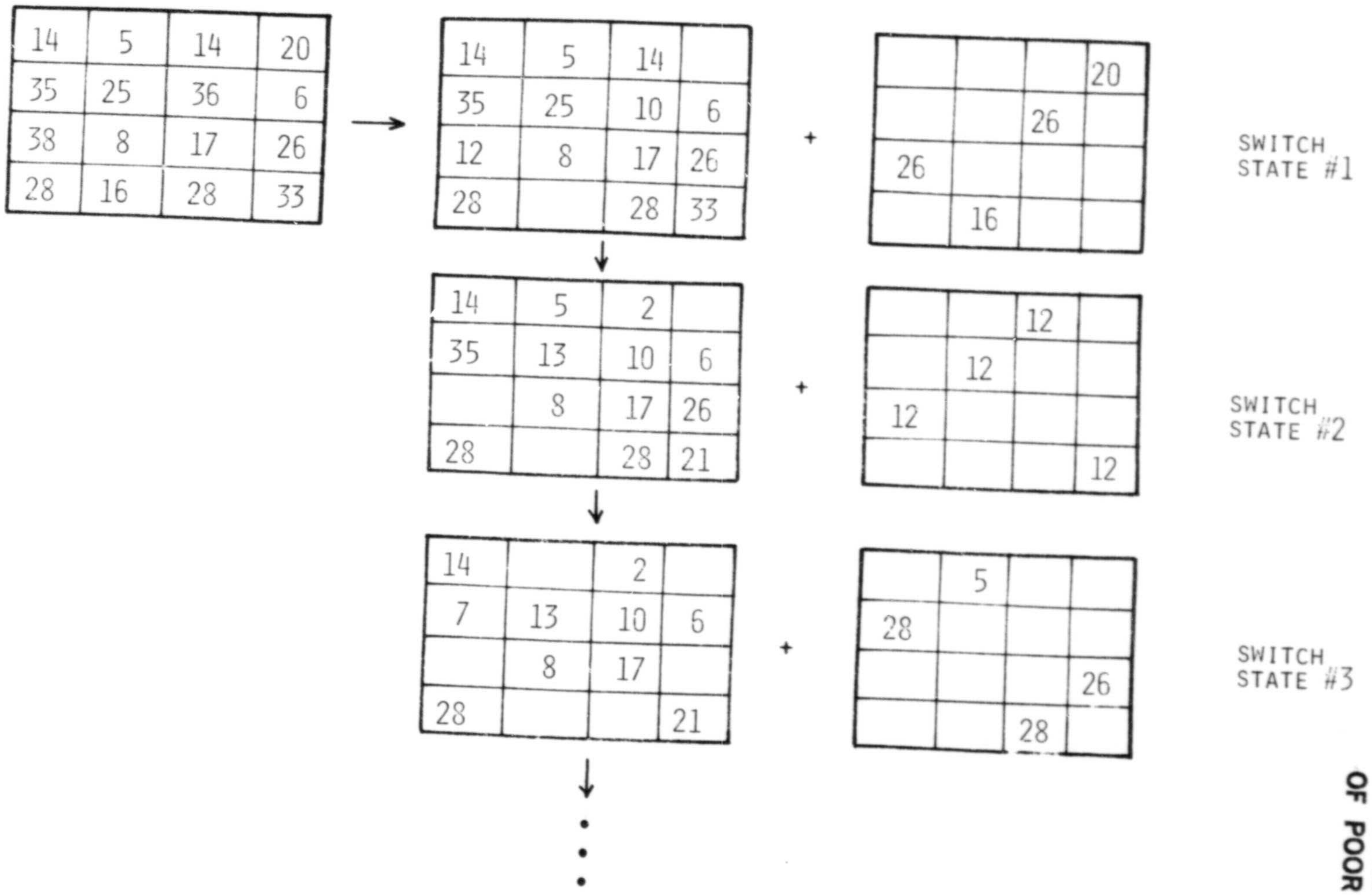

Figure 3-23. Example of Traffic Matrix Decomposition

The above algorithm generates at most $n^2 - 2n + 2$ switch states, where n is the number of beams; in most cases, the number of required switch states is significantly lower than this worst-case bound. For a 4 x 4 switch matrix, 10 switch states are required for network traffic, and 16 switch states are sufficient for both network traffic and orderwire bursts.

3.7 TRUNK FADE DETECTION

Trunk fade detection is complicated by the need to separate up- and down-link effects on a received signal. The down-link (20-GHz) fade can be measured easily using the 20-GHz TT&C beacon and a narrowband tracking receiver as shown in Figure 3-24. Table 3-3 contains a link budget for such an approach and indicates that about 45 dB of operating range is possible.

Table 3-3. 20-GHz Beacon Link Budget for Trunking Station

Beacon Power	0 dBW
Transmit Antenna Gain	30 dB
e.i.r.p.	30 dBW
Path Loss	-210 dB
Receive Antenna Gain (5 m)	58 dB
Receive Signal Power	-122 dBW
System Temperature, T	28 dB
C/kT (k = -228.6 dB/°K)	79 dB
Detection Filter Bandwidth	23 dB-Hz
C/N	56 dB

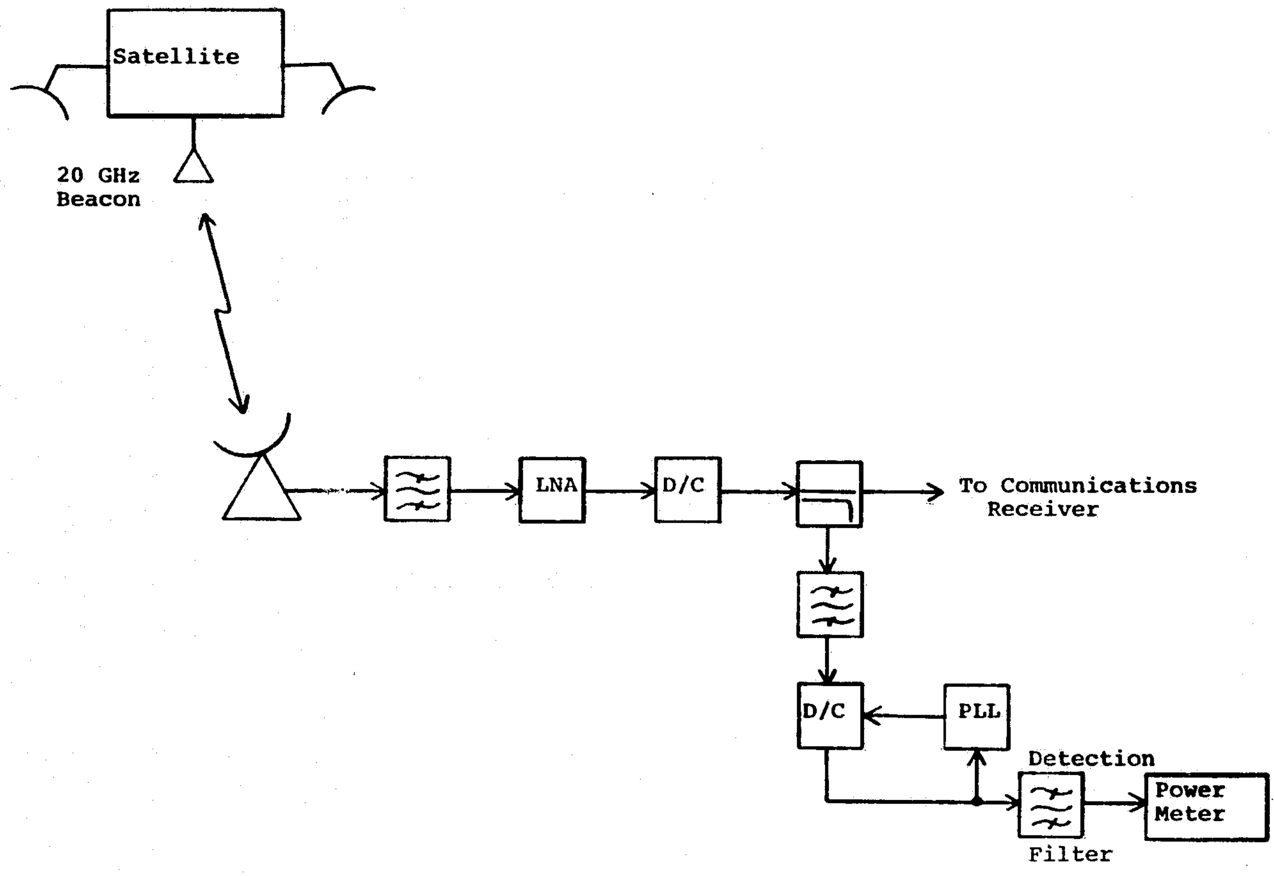

Figure 3-24. 20-GHz Beacon Fade Measurement

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While trunk network down-link path fades can be measured rather easily, up-link path fade detection measurement is complicated by several factors. Although the long-term correlation between 30- and 20-GHz fades is good, the short-term (<10 s) correlation is quite poor. Thus, up-link fades cannot be easily calculated from down-link fade measurements. The nonlinear characteristic of microwave TWT amplifiers prevents calculation of up-link fades based on down-link fade measurements. When the TWTA is operated at or near saturation, up-link power fluctuations of several dB result in much smaller down-link power fluctuations. A typical TWTA input-output characteristic is shown in Figure 3-25, where 1-dB output power degradation represents a 6-dB input power degradation when the tube is operated at saturation. Determination of an up-link fade of 3 dB would require a combined measurement accuracy of less than 0.5 dB, which is impractical.

Two other alternate methods are to provide on-board measurement equipment to directly measure up-link power or install a second beacon on board transmitting at 30 GHz and monitor both beacons at each ground station. The on-board power measurement technique is shown in Figure 3-26. A portion of the IF signal is coupled off, rectified by a diode, filtered, and converted to a digital format. This method is capable of power measurement in less than 1 μs. Separate coupling and measurement equipment for each trunk channel are required, but the total power and weight will be small. Unfortunately, the signal C/N (nominally 20 dB) would have a relatively small useful operating range during fades in excess of 10 dB, and the measurement accuracy would be seriously degraded. Moreover, identification of the originating station would be required on board the spacecraft. In addition, the volume of data which must be sent to the

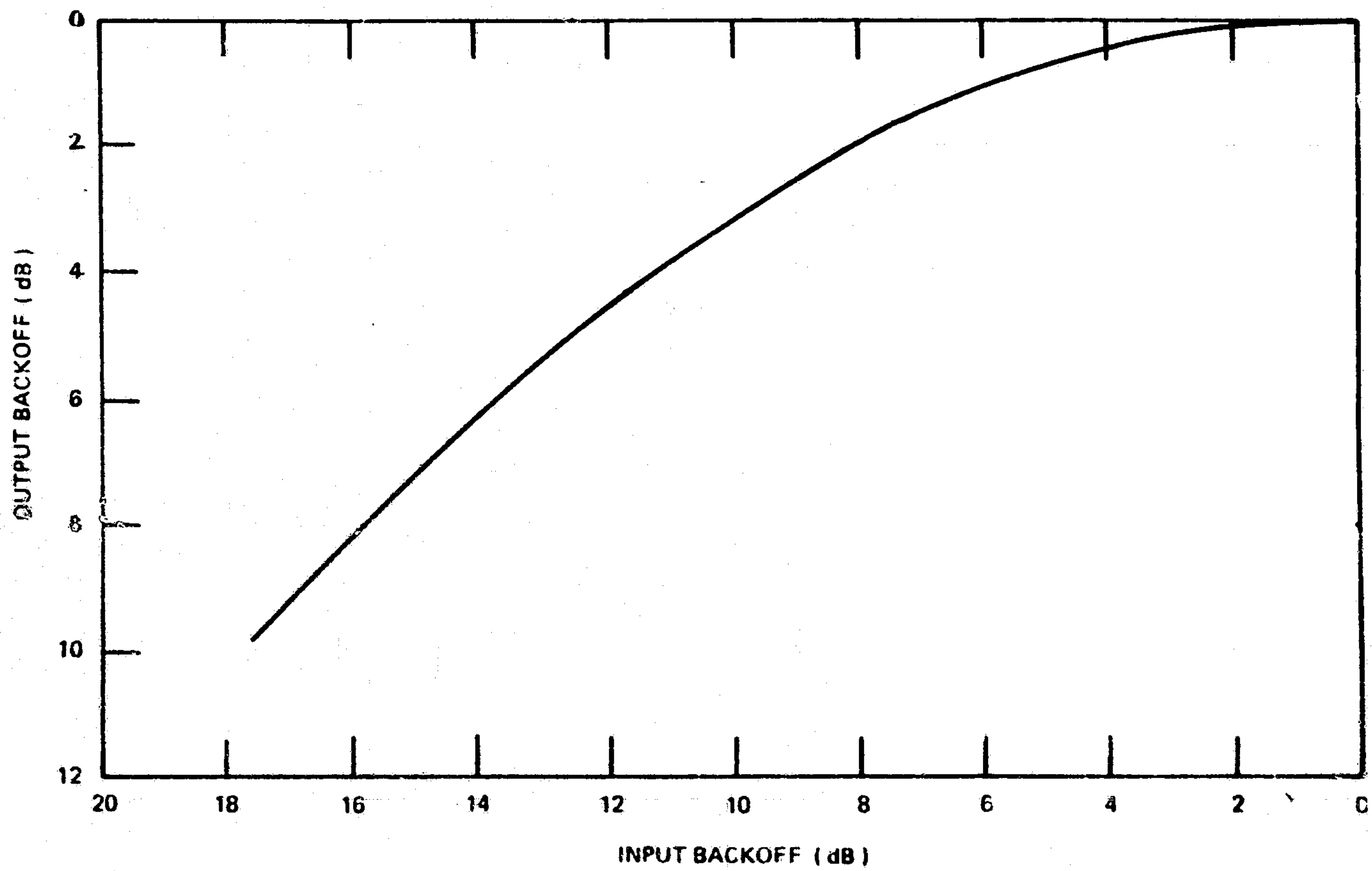

Figure 3-25. Typical TWTA Characteristic

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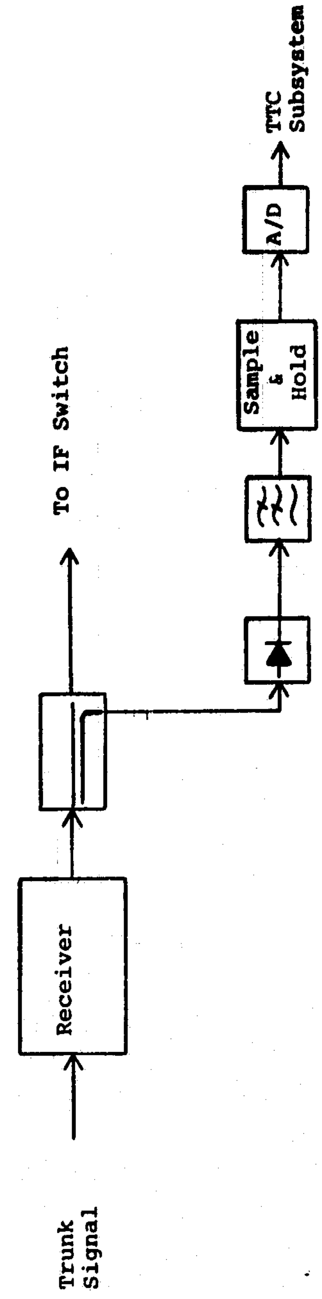

Figure 3-26. On-Board Diode Detector Power Measurement

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MCS does significantly impact the TT&C system. The currently envisioned data rate of some tens of kilobits would be inadequate. The volume of data could be reduced by including some additional processing electronics on board to permit storage and comparison of successive measurements with fade data transmitted only when a significant change has occurred.

A diagram of the beacon method is shown in Figure 3-27. A second beacon, transmitting at 30 GHz, is installed on the satellite. The level of this beacon is measured at each site to determine the rain fade. This method is complicated by the need to receive the 30-GHz beacon simultaneous with the transmission of 30-GHz communications traffic. Care must be taken to prevent overloading the receive LNA with leakage from the transmit side and degrading its noise figure. Figure 3-28 shows the conventional hardware configuration to isolate the receive and transmit paths. The HPA output is filtered to remove spurious out-of-band products. The orthomode transducer (OMT) provides typically 35-dB isolation between the orthogonal transmit and receive polarizations. Since the maximum trunk transmit power is 28 dBW and the typical maximum LNA input level is -70 dBW, the transmit reject filter must supply 63 dB of transmit attenuation. Ordinarily this is no problem since the receive and transmit band separation is wide with respect to the receive bandwidth. Accurate fade measurement, however, requires that the 30-GHz band beacon be very close to the transmit band. A practical filter which would pass both the receive band and the beacon and also provide the required transmit band rejection would require moving the beacon substantially toward the receive band and would seriously impair the accuracy of the measurement. In the experimental system, sufficient frequency separation could be selected between the 30-GHz beacon and the transponder receive frequencies

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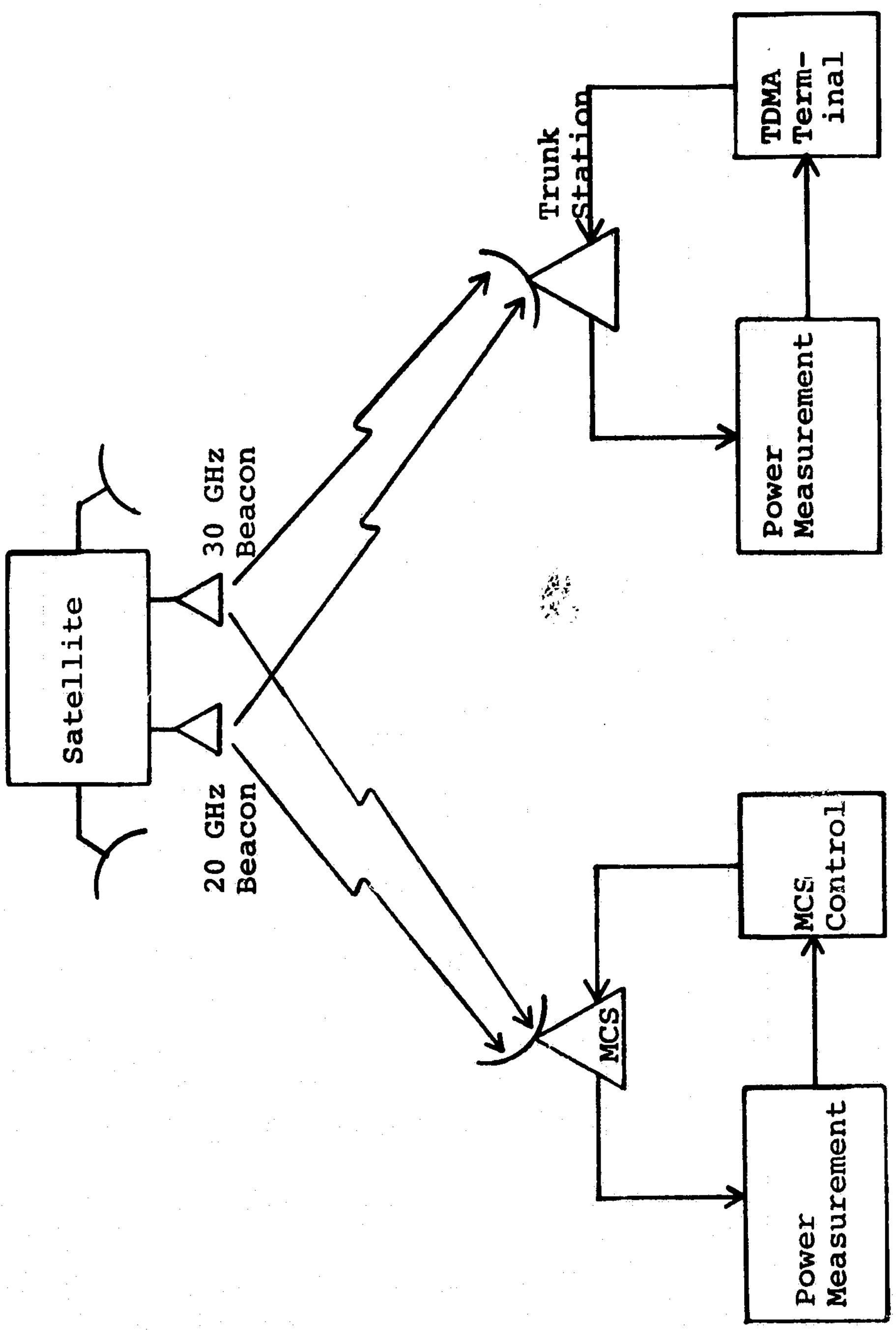

Figure 3-27. Fade Detection With Dual Beacons

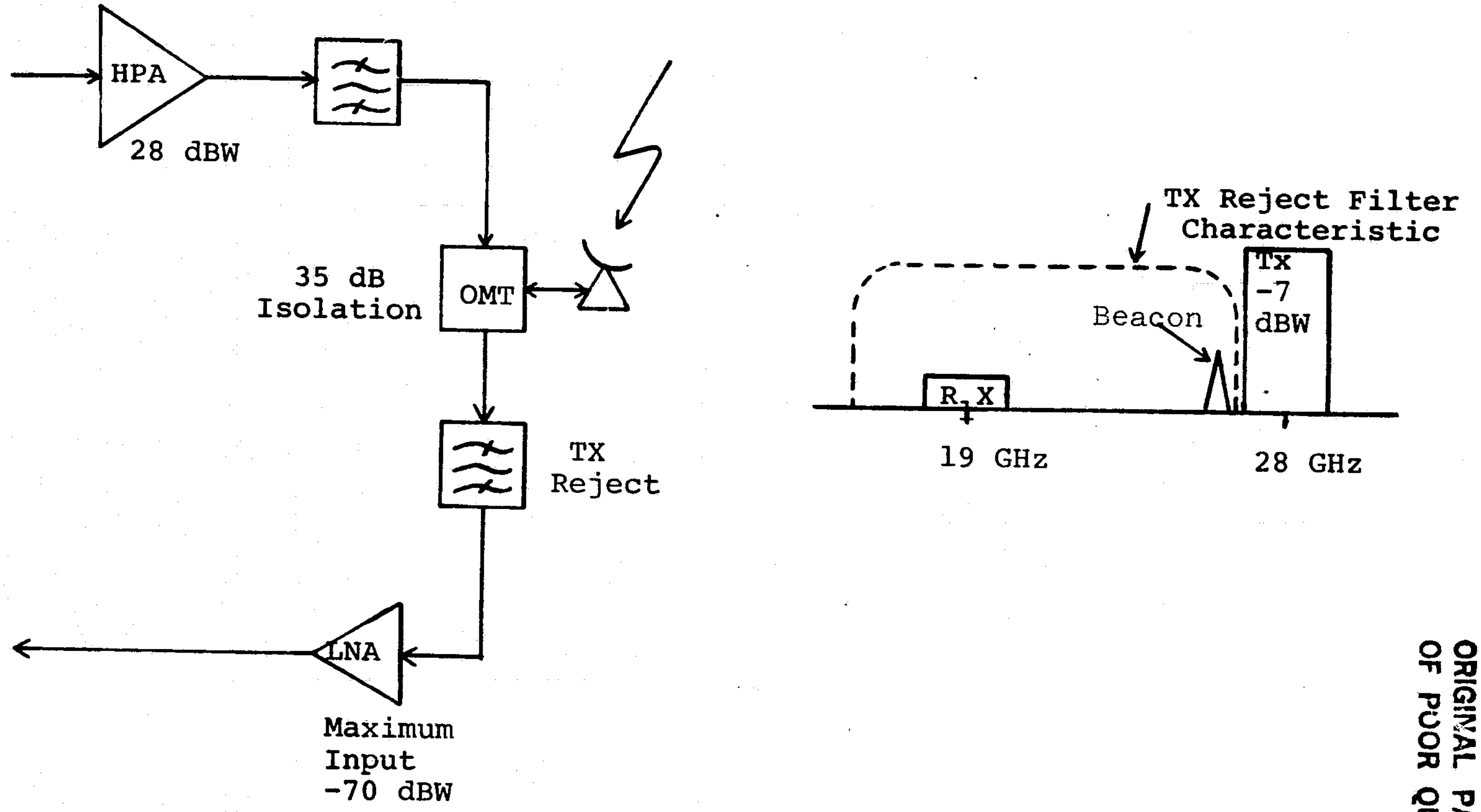

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Figure 3-28. Receiver - Transmit Isolation since only a small portion of the 2500-MHz band is used for communications.

If a sufficient beacon signal-to-noise ratio exists, another approach, shown in Figure 3-29, is feasible. A portion of the receive power can be coupled off, and a narrowband filter is used to provide the required rejection. After amplification, the signal is down-converted using a narrowband phase-locked loop (PLL) for tracking. A very narrow pre-detection filter may be used to recover the C/N loss resulting from the coupler. A link budget for such a scheme is given in Table 3-4. A C/N of 42 dB would permit fades of up to 30 dB before the measurement accuracy becomes seriously degraded. The PLL would remain in lock during fades of up to 42 dB, and accurate measurement could resume when the fade abated.

Table 3-4. 30-GHz Beacon Link Budget for Trunking Station

Beacon Power	0 dBW
Transmit Antenna Gain	30 dB
e.i.r.p	30 dBW
Path Loss	-213 dB
Receive Antenna Gain	67 dB
Receive Signal Power	-116 dB
Coupling Loss	20 dB
System Temperature, T	28 dB
C/kT (k = -228.6 dB/°K)	65 dB
PLL Bandwidth	23 dB-Hz
C/N	42 dB

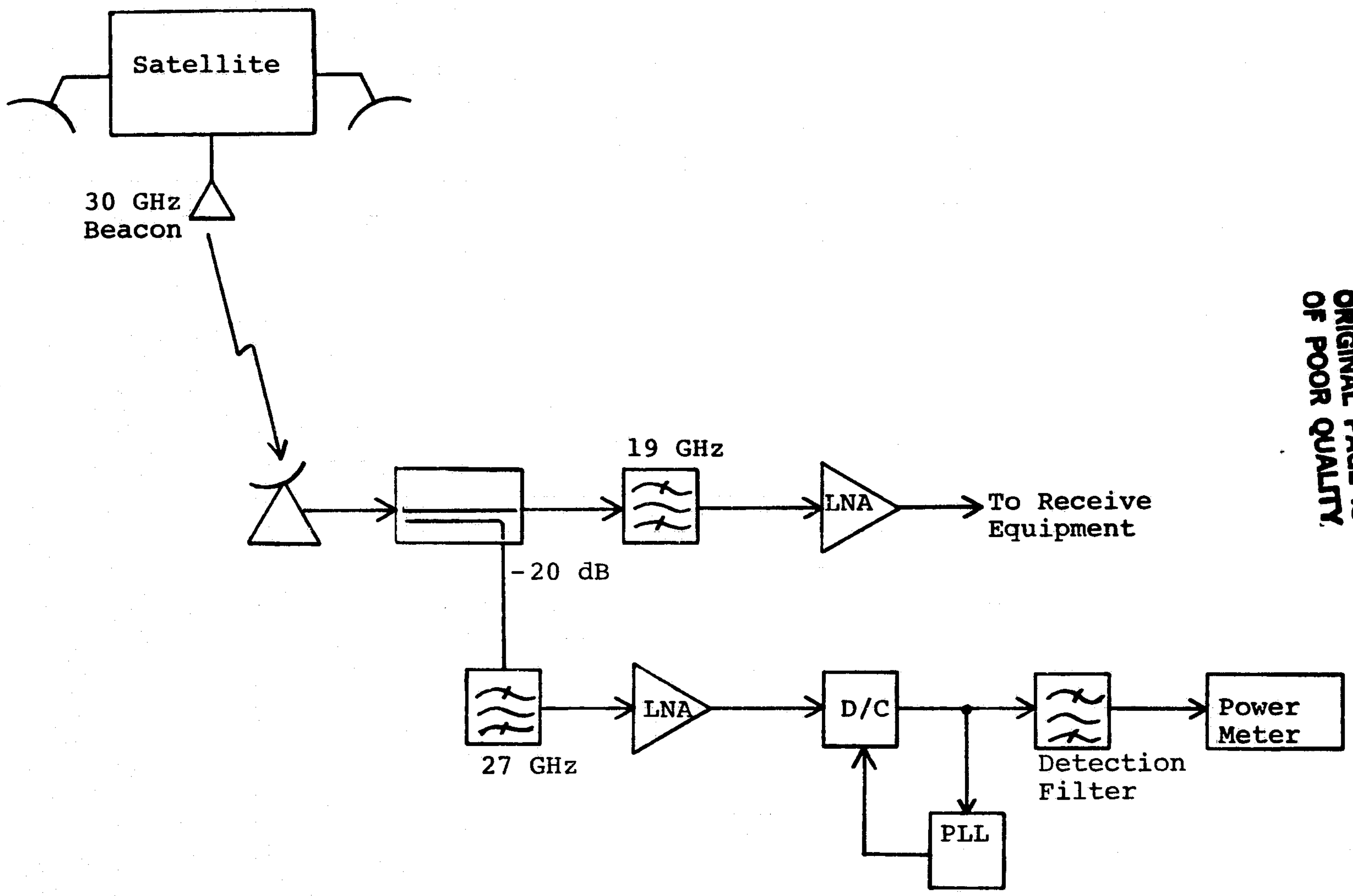

Figure 3-29. 30-GHz Beacon Power Measurement

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The two methods described above are compared in Table 3-5. The on-board measurement method requires measurement electronics for each channel on board, high-speed burst power measurement, and a significant increase in the TT&C link capacity. It has the advantage of measuring the fade directly, using the actual signal, and will provide faster adaptation response time since transmission of fade data can occur without waiting for an assigned orderwire slot and involves only one earth-satellite path delay. The disadvantage of this method is a relatively small operating range. During large fades it would be unusable.

Table 3-5. Comparison of On-Board Measurement and Beacon Methods

	On-Board Measurement	Beacon
Advantages	• Simpler earth station hardware • Faster response • Direct signal power measurement • Less satellite power and weight consumption	• >30 dB operating range • Measurement of continuous signal
Disadvantages	• High-speed on-board electronics • High data rate telemetry link • 10-dB operating range	• Indirect measurement • Greater satellite power and weight requirements • Slower response • More complex earth station hardware

The beacon method would probably entail greater power and weight costs for generation of a stable 30-GHz beacon of reasonable power (1 W); however, it would provide a much greater useful measurement range. Based on this comparison, it is recommended that the beacon method be implemented in the experimental system. The suggested up-link and down-link fade detection system is shown in Figure 3-30.

3.8 ADAPTIVE POWER CONTROL

Based on the up-link and down-link power measurements made by the fade detection system described in Subsection 3.7, the MCS adjusts trunk station transmit power levels via the orderwire channel and satellite transmit power via the TT&C link. When measurements made by the MCS indicate that the up-link fade has exceeded a predetermined threshold, the MCS instructs (via the orderwire) the terminal to increase its up-link power. Similarly, when the fade abates, the terminal is instructed to lower its transmit power. On-board transmit power is controlled via the TT&C system. This process is shown in Figure 3-31. Variation of power is effected by varying the drive to the HPA using PIN diode attenuators which have switching times in the nanosecond range. The attenuators are controlled by the terminal control processor. When fades occur which are too great to be compensated for by power control, diversity switching occurs.

Table 3-6 gives a breakdown of the delays which make up the system response time. The orderwire waits are the worst-case delays until the terminal must use the shared orderwire slots for fade data transmission. As indicated, the worst-case delay is 2 seconds, which corresponds to a maximum fade of 2-dB up-link

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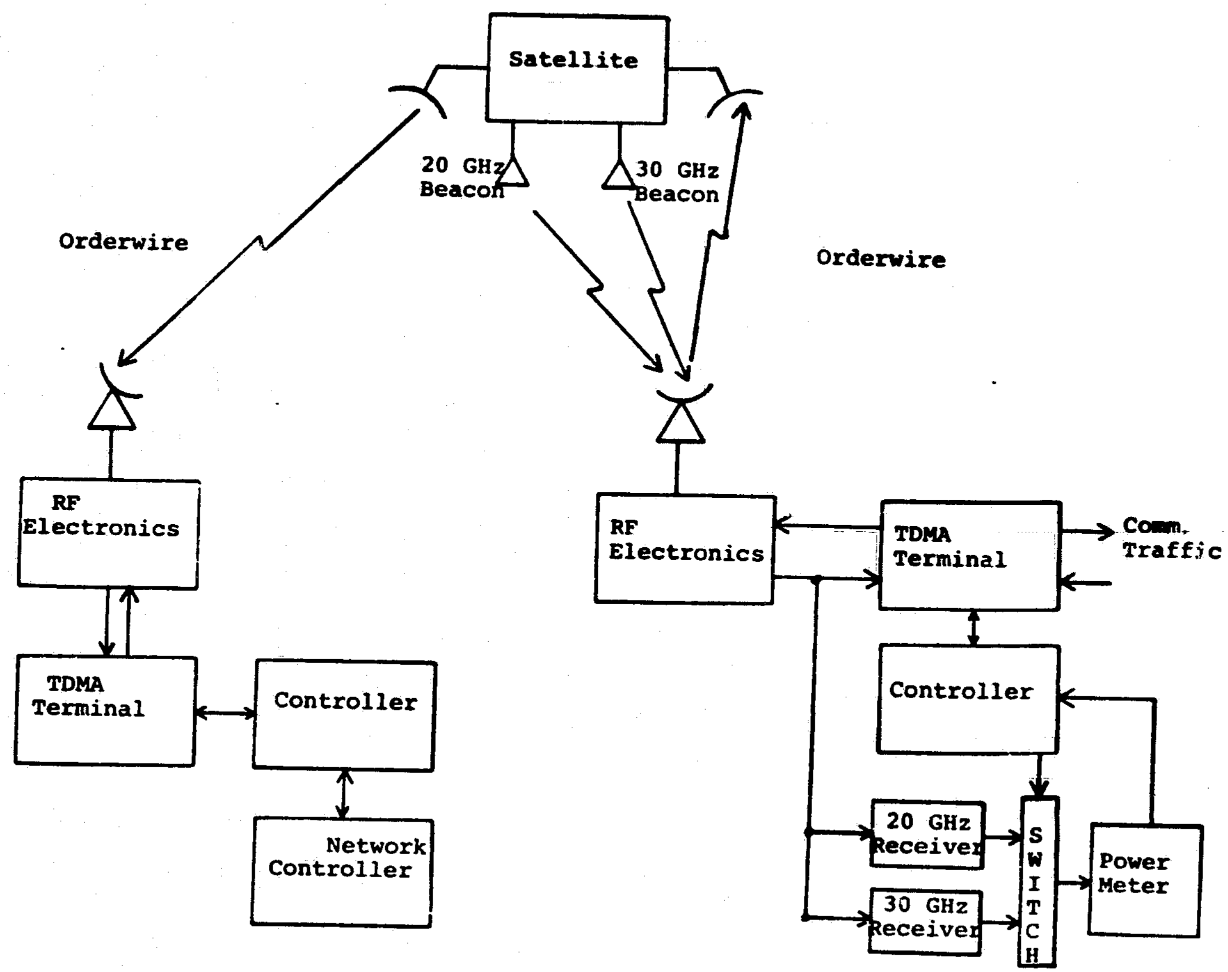

Figure 3-30. Trunk Fade Detection

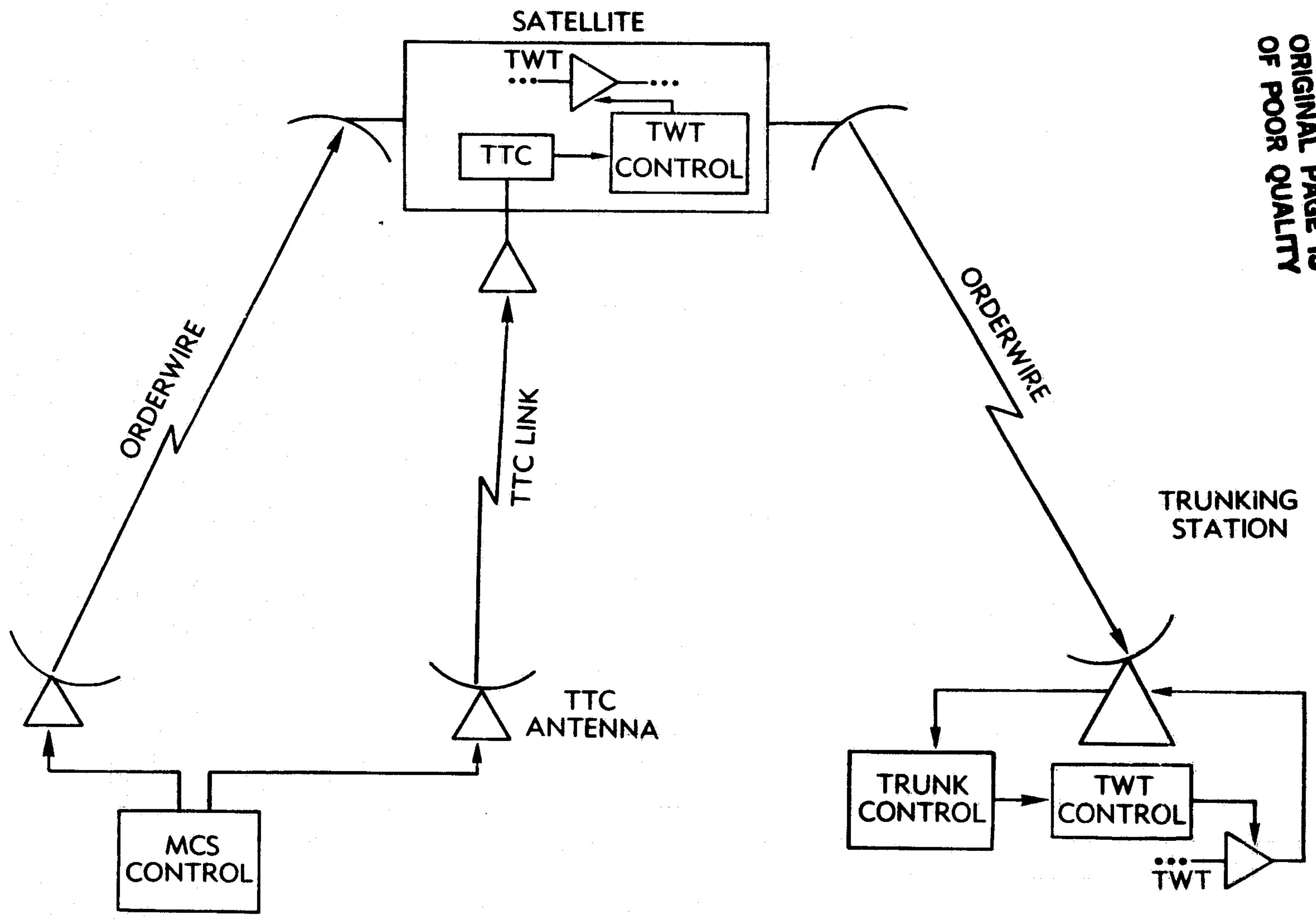

Figure 3-31. Trunk Network Power Control

and 1-dB down-link. These represent the minimum required link margins to be provided without adaptive compensation.

Table 3-6. Worst-Case Adaptive Power Control Response Time

Station Orderwire Wait	1.0 s
Propagation Delay	0.25 s
MCS Orderwire Wait	0.5 s
Propagation Delay	0.25 s
Total	2.0 s

3.9 ON-BOARD OSCILLATOR CONTROL

The on-board oscillator in an SS-TDMA network supplies reference timing to the IF switch distribution control unit, and the trunking station must in turn synchronize its burst transmission to the on-board switch-state timing so that all bursts arrive at the satellite at the proper instant. Thus, the on-board clock becomes the reference timing source for a satellite network, and its stability directly affects networks operation.

A high-stability on-board clock is not only desirable for the TDMA synchronization process, but it is also necessary for interconnecting various satellite and terrestrial networks. The following are three approaches that implement high-stability on-board timing:

a. On-board atomic clock
b. On-board phase-locked loop: reference tone transmission or reference burst transmission

c. Clock drift measurement/correction: SS-TDMA synchronization burst method or down-link reference burst (or beacon) method

The on-board atomic clock approach is ideal; however, the other two approaches seem to be more desirable in terms of spacecraft weight, power, and reliability.

An alternate approach to an on-board atomic clock employs a voltage-controlled crystal oscillator (VCXO) on the satellite and controls its drift either by phase locking the frequency source to the reference signal transmitted from the ground or by measuring the clock drift on the ground and periodically sending correction information to the satellite. In either case, the long-term stability of an earth station high-stability reference clock is transferred to the on-board oscillator, and any short-term drift is absorbed by an earth station buffer.

The on-board phase-locked-loop method is rather vulnerable to transmission link interference since one clock slip may cause a loss of synchronization and a subsequent temporary system outage. A complex clock monitoring system is required on the ground as well as on the satellite. In addition, a larger earth station buffer may be needed to absorb the up-link Doppler effect on the on-board oscillator. The clock drift measurement/correction approach requires simple on-board hardware, i.e., a digital-to-analog converter and a VCXO, and its ground control system is easily implemented. On-board clock drift is measured using SS-TDMA synchronization bursts in the trunk network or down-link reference bursts in the CPS system.

3.9.1 ON-BOARD CLOCK CORRECTION BY DRIFT MEASUREMENTS

A simple on-board clock control diagram for the trunk network is shown in Figure 3-32 [18],[19]. On-board clock drift is easily measured at the MCS using sync bursts. The MCS transmits a sync burst to the synchronization window, and its intersection with the trailing edge of the window is detected at the MCS by comparing a stored bit pattern and received bit pattern of the metering segment. Sixty-four successive bursts are used to determine the exact intersection position with a low error probability. The phase error measuring circuit measures the displacement between the nominal and detected trailing edge intersection positions. The measurement, x_i, is supplied to both the transmit timing generator and to an accumulator. The transmit timing generator immediately makes a displacement correction in the amount x_i to realign its burst transmission in an attempt to reduce the displacement error to zero.

Values of x_i can be updated with a period no less than the round-trip propagation time to the satellite plus the duration of the measurement smoothing interval. The value of x_i is also accumulated over an interval of T_O seconds and the phase error s_k, is calculated. Then the clock correction datum, w, is computed from s_k and transmitted to the satellite via the telemetry link to update the VCXO control voltage. The clock correction interval, T_O, can range from a few hours to several days depending on the system requirement.

The Doppler effect is removed from s_k by calculating the range variation during the measurement interval or minimized by selecting a sidereal day correction interval, T_O = 86,164 s.

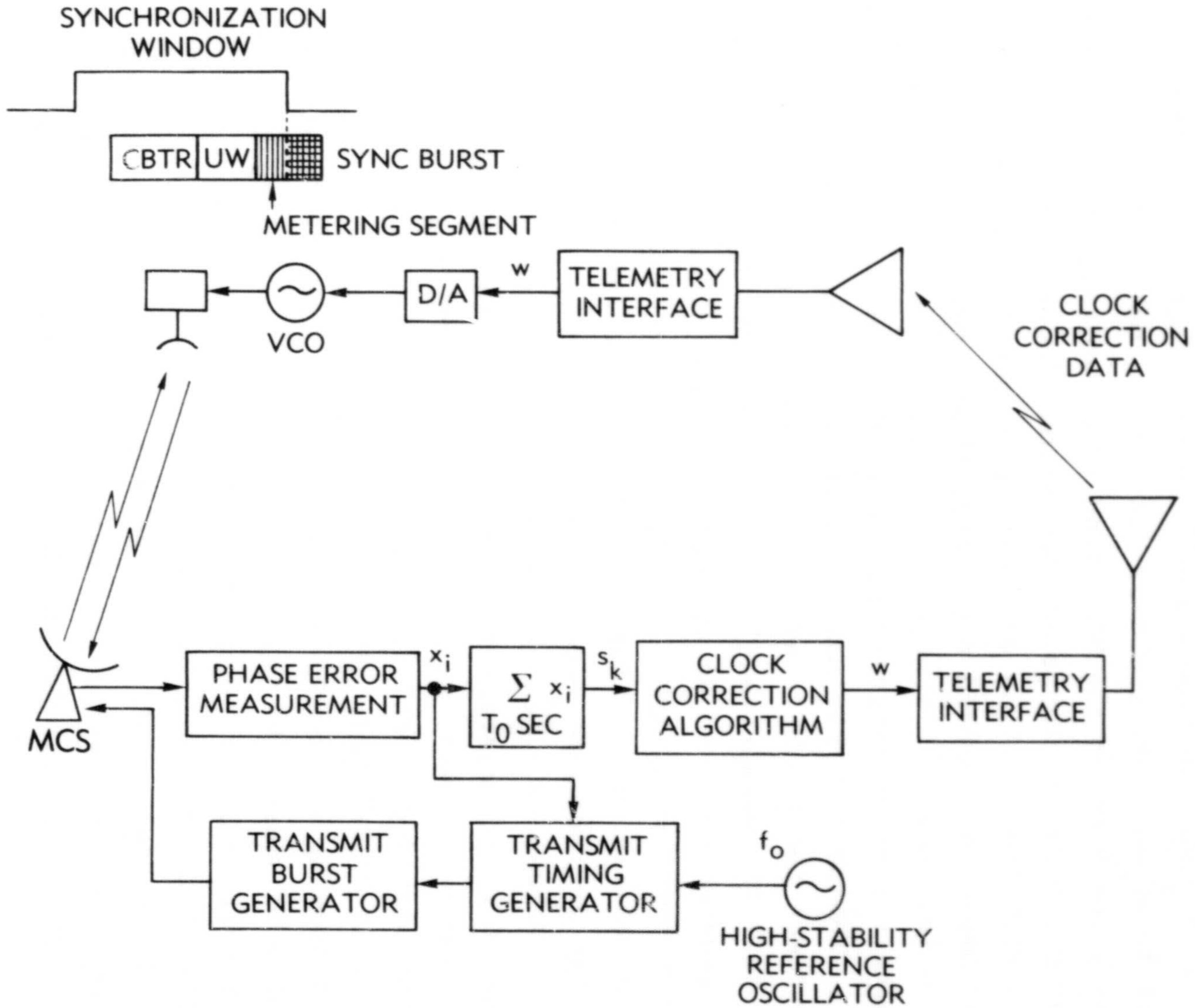

Figure 3-32. On-Board Clock Correction by Drift Measurements

3.9.2 CLOCK CORRECTION ALGORITHMS

Two clock correction algorithms are the optimum correction method and the drift prediction method. The first algorithm is optimized for an arbitrary clock drift which does not exceed a certain value over one correction interval, whereas the second algorithm is more efficient for almost linear drift. Depending on the clock drift characteristics, either method can be employed.

The optimum correction method [20] is illustrated in Figure 3-33. The phase error measurement, s_k, is accumulated in Σ_1 over the entire period to detect a long-term clock drift. The accumulator content, y_k, is then added to s_k in Σ_2, resulting in the kth incremental phase correction u_k. This additional s_k may be regarded as the correction term of the kth interval phase error. Accumulator Σ_2 is the summation of successive incremental phase corrections and compensates for the on-board clock drift in the (k + 1)st interval. This algorithm yields the maximum phase error of eT_o, where e is the worst-case drift over one correction period.

The drift prediction method [21] is shown in Figure 3-34. Periodic phase error measurements generate cumulative phase error values of y_0, y_1, ..., y_n, and these measured phase errors are curve-fitted by a polynominal function by minimizing a mean-square error. The polynominal function is then used to predict the drift in the next correction interval. The incremental correction value, Δw, is selected so that the estimated cumulative phase error becomes zero at the end of the next correction period. This algorithm allows the successive correction intervals to be any integer multiples of the phase error measurement period T_o.

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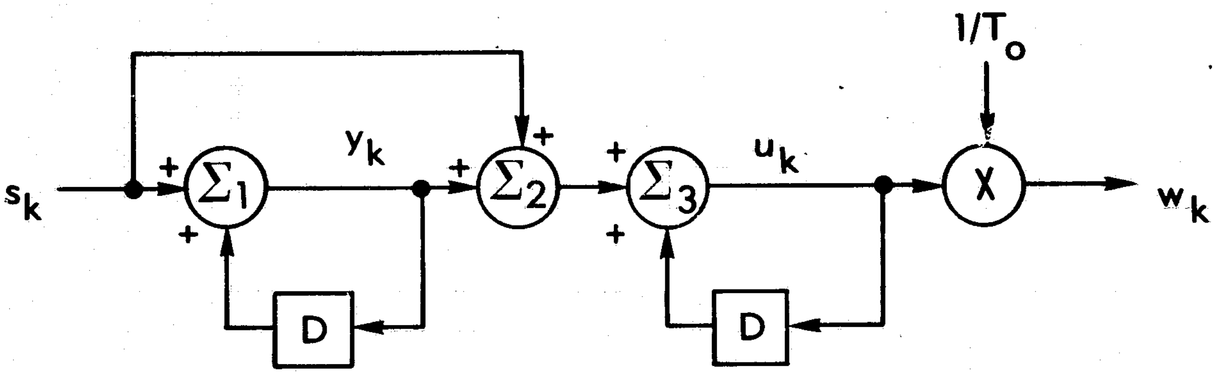

Figure 3-33. Optimum Correction Method for Arbitrary Drift

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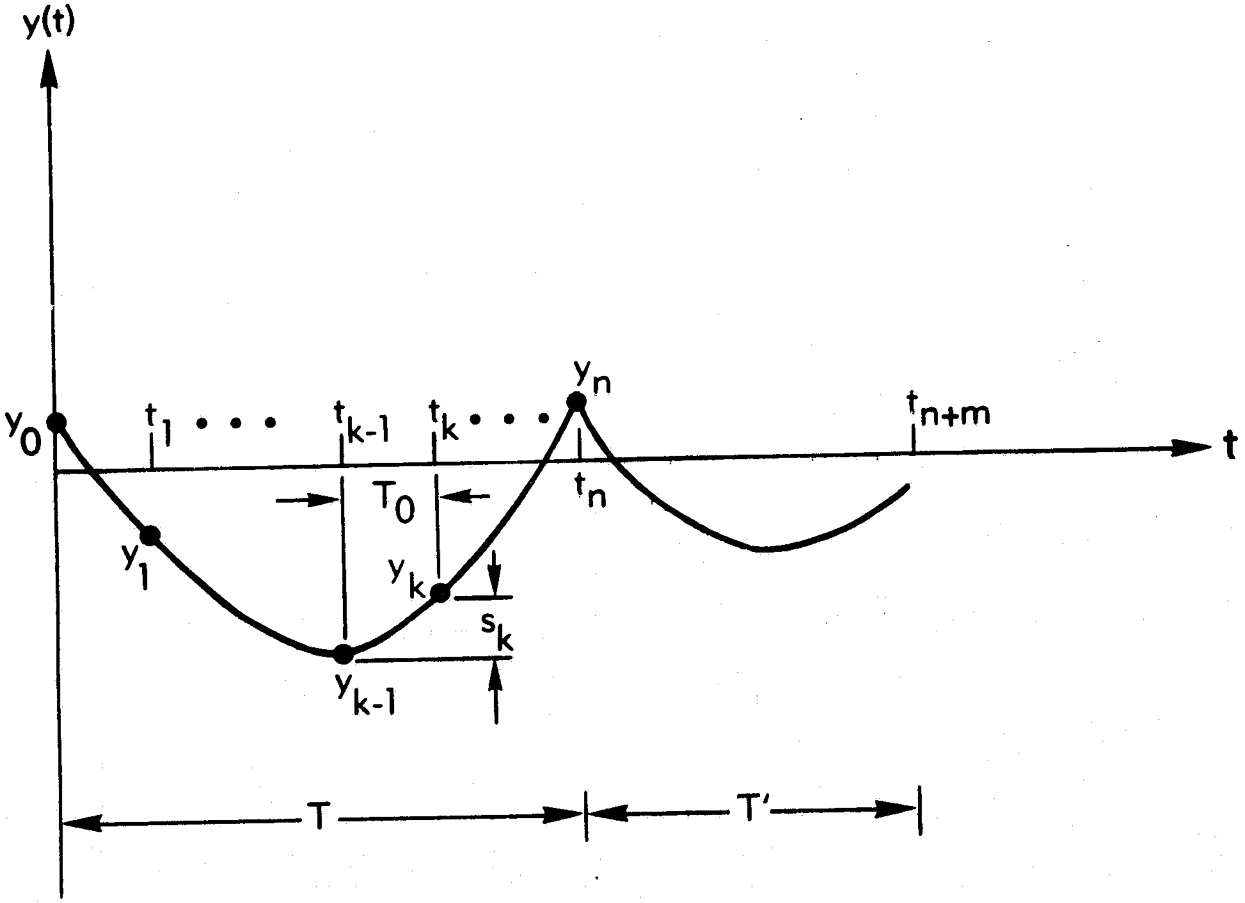

Figure 3-34. Drift Prediction Method Based on Polynomial Approximation

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3.10 TERRESTRIAL NETWORK TIMING

3.10.1 SYNCHRONOUS NETWORK CONNECTION

Terrestrial network timing for a synchronous network connection is shown in Figure 3-35. All the terrestrial network clocks are synchronized or slaved to the on-board clock, f_s. On-board timing experiences down-link Doppler shift when transmitted to the ground, and the received frequency at the earth station of network 1 becomes $f_s(1 - d)$, where d is the satellite Doppler shift. The recovered clock becomes the master clock for network 1, and all data communications equipment in the network is slaved to this clock. Since earth station transmit timing is synchronized to the on-board timing, its frequency must be $f_s(1 + d)$ to compensate for the Doppler effect. The instantaneous frequency offset between the network clock and earth station transmit clock is absorbed by an earth station buffer. The required buffer size is approximately 280 μs, and no data loss is expected in the normal operation.

This type of network connection is useful for a small CPS network which can drive its network timing from an earth station clock.

3.10.2 ASYNCHRONOUS NETWORK CONNECTION

The asynchronous network connection, shown in Figure 3-36, employs a bit stuffing/destuffing technique to compensate for the timing offset between the terrestrial network clock and the earth station transmit clock [22]. However, an earth station buffer is needed at the receive side to absorb the

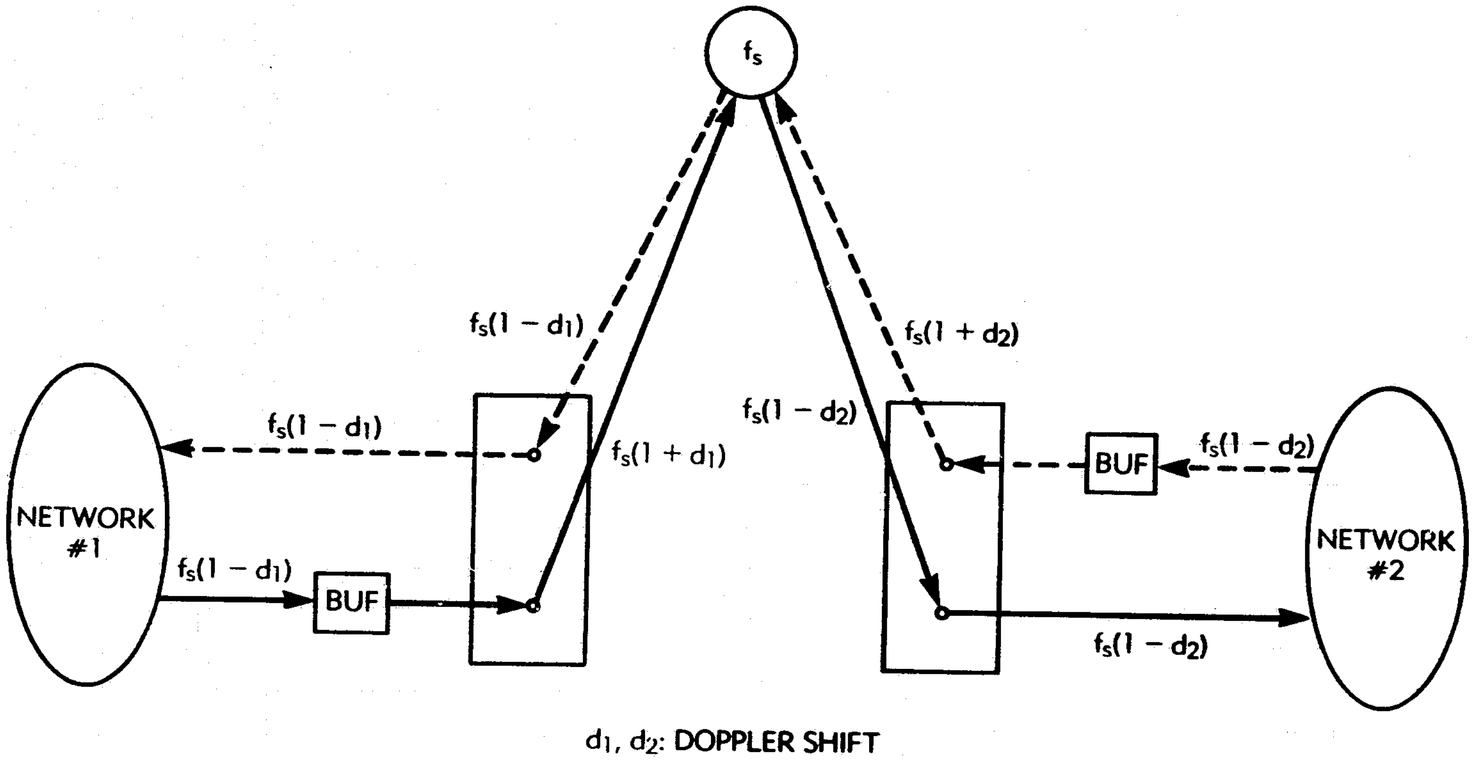
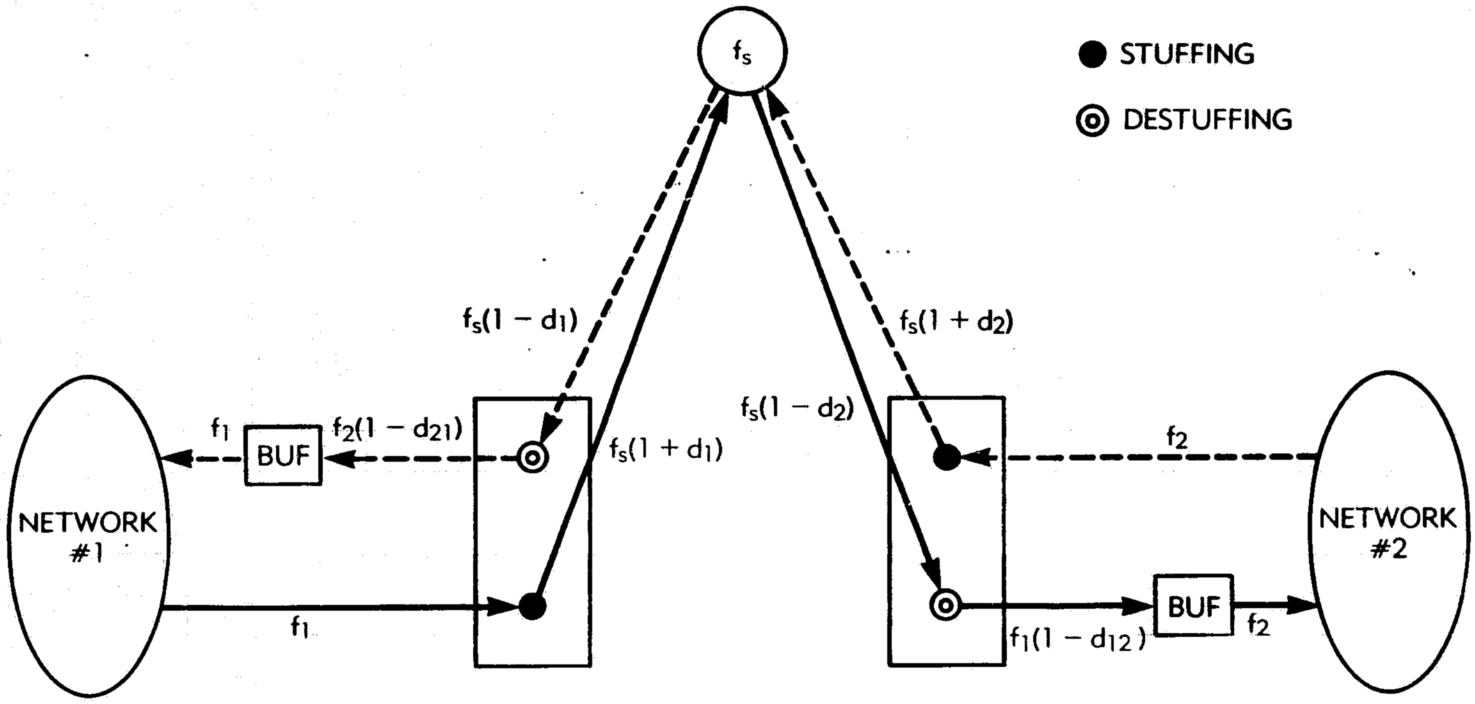


Figure 3-35. Synchronous Network Connection



d_1, d_2: DOPPLER SHIFT

$$d_{12} = f_s(d_1 + d_2)/f_1 \cong d_1+d_2$$
$$d_{21} = f_s(d_1 + d_2)/f_2 \cong d_1+d_2$$

Figure 3-36. Asynchronous Network Connection

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Doppler shift and frequency offset of terrestrial network clocks. In addition to a 280-μs Doppler buffer, a frame alignment buffer is required for digital terrestrial link interference. The frequency of buffer overflow/underflow is a function of the frequency error of terrestrial network clocks.

Asynchronous network connection is useful when all the terrestrial networks are synchronous with a bounded phase error. Otherwise, the plesiochronous connection described in the next subsection is more desirable.

3.10.3 PLESIOCHRONOUS NETWORK CONNECTION

The satellite and terrestrial networks have high-stability clocks with an accuracy of on the order of one part in 10^{11}, and independent timing relationships. The timing error caused by the Doppler shift and frequency offset is adjusted by earth station transmit and receive buffers [23],[24]. Each buffer must include the Doppler effect (140 μs), frame alignment component, and short-term on-board clock drift term. Figure 3-37 illustrates plesiochronous network connection.

A plesiochronous network is particularly useful for the trunk and large CPS networks, and can coexist with synchronous CPS networks.

3.11 TERRESTRIAL NETWORK CONTROL

An important issue in the satellite enhancement of the public telephone trunk network is how to extend current trunk assignment and signaling methods to operate with the satellite

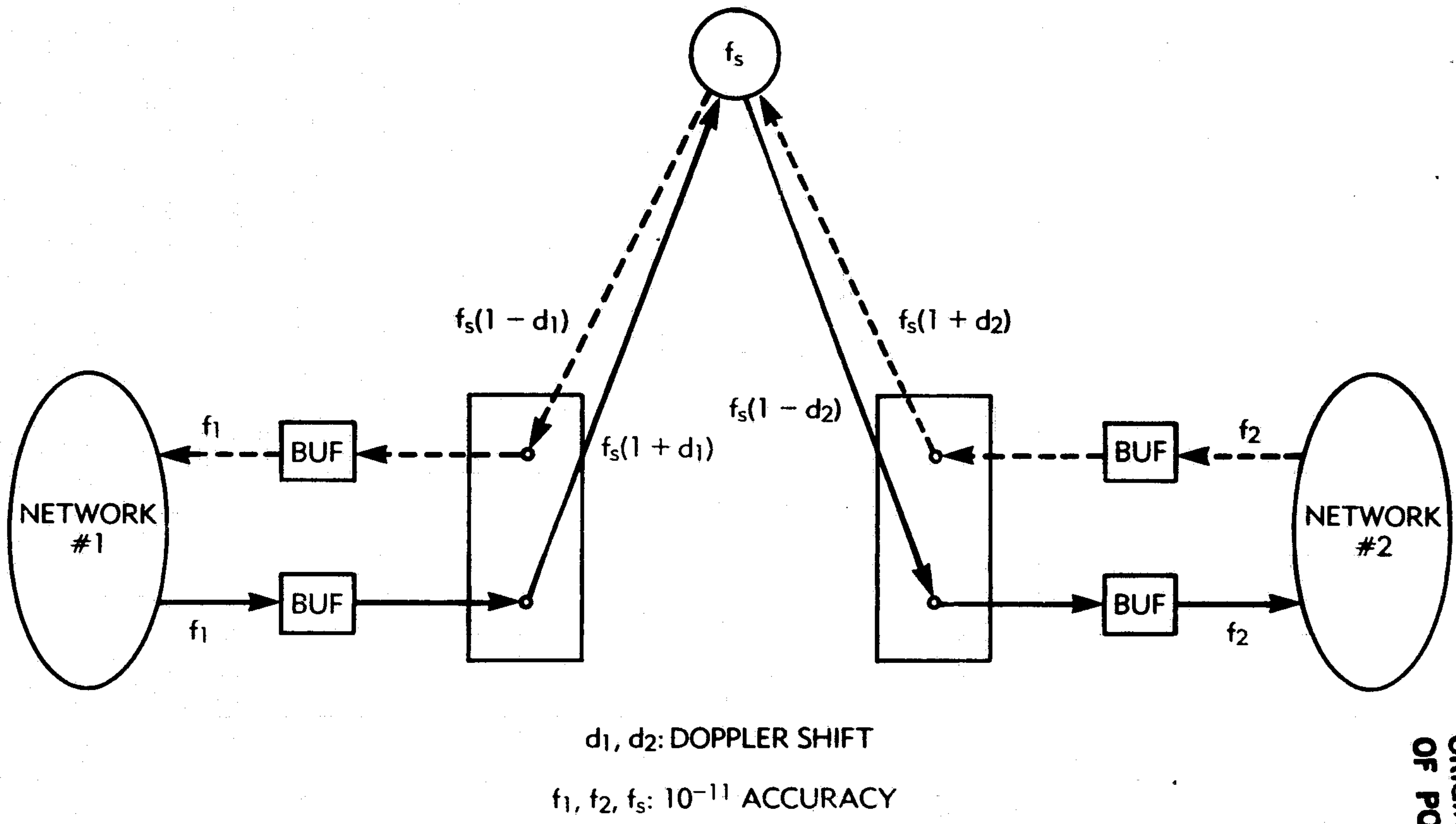

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Figure 3-37. Plesiochronous Network Connection system. The long-distance trunk system is making increasing use of stored-program control (SPC) exchanges and the common-signaling-channel method (CSC) [25],[26]. Within the Bell system, the signaling method is called Common Channel Interoffice Signaling (CCIS) [27].

3.11.1 CCIS SIGNALING METHOD

In contrast with the older per-trunk signaling methods, the CCIS system employs a separate digital channel which manages the trunks between the exchanges. In the "associated" mode (Figure 3-38), the CCIS channel is dedicated to a single exchange pair, whereas in the nonassociated mode the signaling channel may run via a third exchange.

3.11.2 TRUNK ASSIGNMENT STRATEGIES

The two fundamental strategies for assigning terrestrial trunks to remote exchanges via satellite are fixed and demand assignment. With fixed assignment, currently the primary method in the INTELSAT system, a specific number of trunk circuits are permanently assigned between any exchange and the corresponding remote exchanges (Figure 3-39). The circuits are maintained over periods of months. Changes are instituted only gradually, mainly because of grade-of-service sensitivity to FDMA carrier frequencies and carrier-power levels.

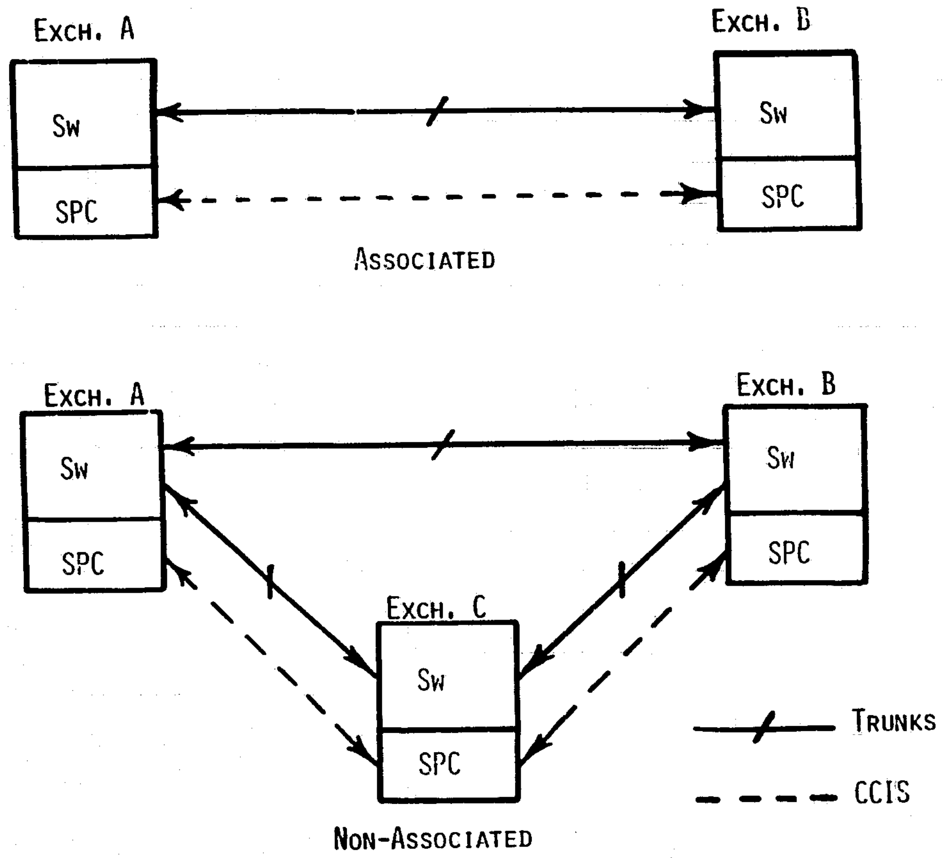

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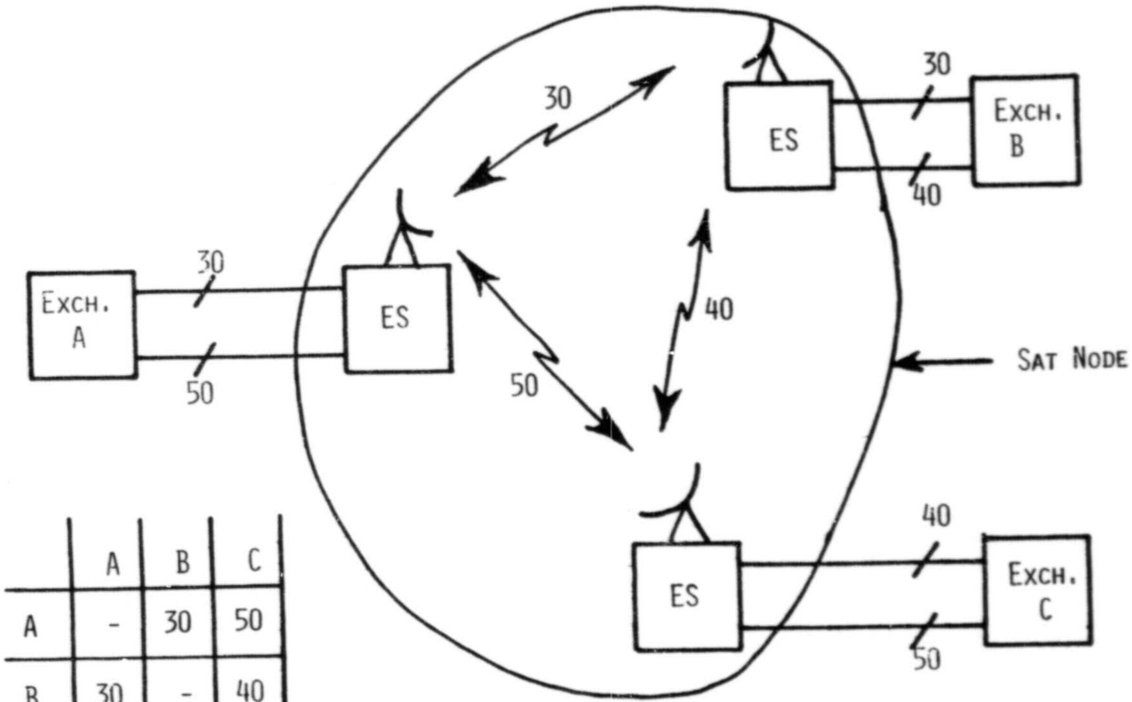
Figure 3-38. Trunk Control With CCIS



	A	B	C
A	-	30	50
B	30	-	40
C	50	40	-

TRUNK MATRIX

Figure 3-39. Fixed Assigned Terrestrial Channels

With demand assignment, such as that used in INTELSAT's SPADE system and also in the SBS TDMA system, the terrestrial channel connectivity can be rapidly reconfigured under computer control to accommodate fluctuations in traffic intensity.

3.11.3 RATIONALE FOR NASA DEMAND ASSIGNMENT

The main reason for demand assignment in the NASA experimental system is to assure maximum use of satellite resources during the four characteristic diurnal periods of east-west traffic:

a. East-busy period 0800-1200 EST (0500-0900 PST)
b. East-west period 1200-1700 EST (0900-1400 PST)
c. West-busy period 1700-2000 EST (1400-1700 PST)
d. Night period 2000-0800 EST (1700-0500 PST)

Another reason for specifying demand assignment is that the associated CCIS by itself presumably does not allow point-to-multipoint trunk operation. The problem is illustrated in Figure 3-40. All satellite trunks originating at one exchange terminate at a single corresponding exchange because presumably CCIS is not compatible with the split-trunk operation in Figure 3-39. Associated CCIS operation appears to limit the connectivity of N exchanges to the N/2 corresponding pairs. Clearly, in this figure, it would be preferred to have the full N(N - 1)/2 connectivity of the standard mesh network.

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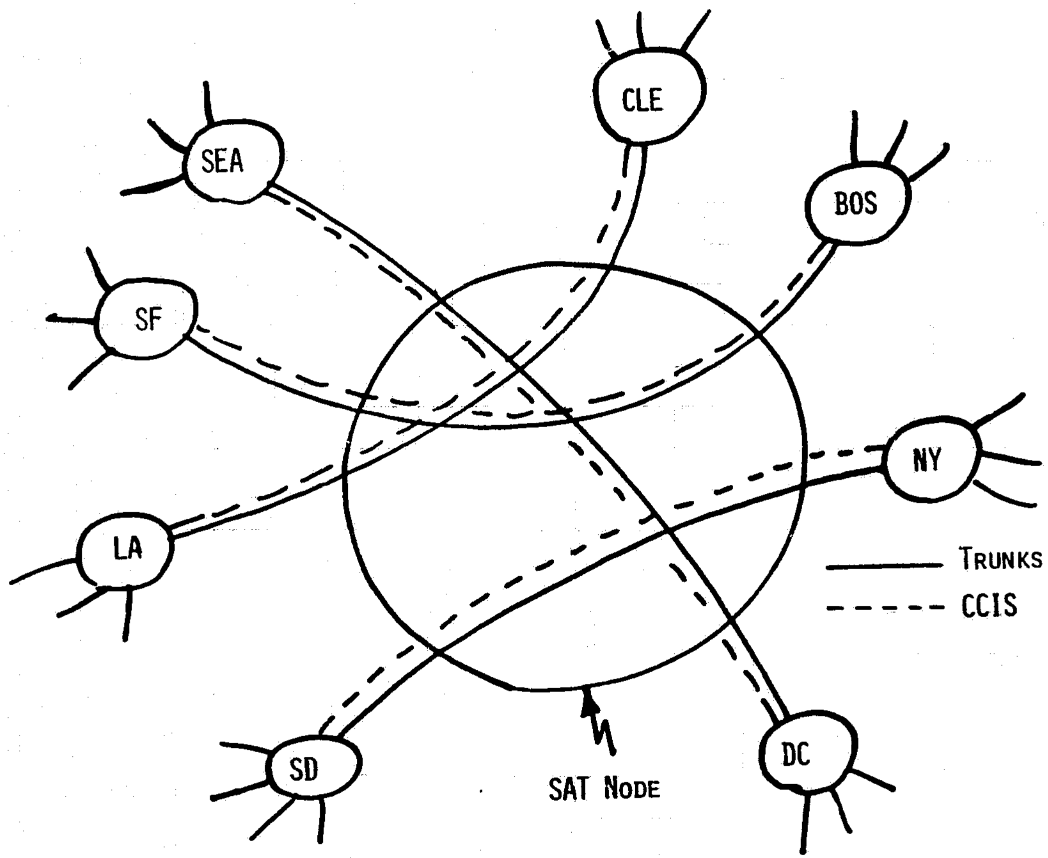

Figure 3-40. Associated Satellite CCIS

C-2

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3.11.4 SATELLITE CCIS SIGNALING

In the older method of fixed trunk assignment (Figure 3-39), the per-trunk signals (seizure, dialing, etc.) are simply passed along on the fixed-assigned voice circuits. There is no switching and signaling within the satellite system. Such direct interoffice signaling with CCIS via the satellite would lower the signaling throughput because of the Go-back-N ARQ procedure used to detect and correct errors in the CCIS channel. If any signaling unit (SU) is received in error, the whole multi-unit message (MUM) must be retransmitted from the source. Thus, FEC is the preferred method of error correction. It appears, however, that most of the standard signal definitions of Bell's CCIS system (LSU, ISU, SSU, etc.) can be extended to an equivalent satellite CSC.

3.11.5 NASA TRUNK GATEWAY SYSTEM

The preferred NASA trunk system (Figure 3-41) uses a signaling strategy similar to that in INTELSAT's SPADE system. The trunk offices interface to the satellite system via trunk gateways (TG). A gateway appears to the terrestrial trunk office like any other terrestrial exchange. The trunk office signals to the NASA gateway by either associated or nonassociated CCIS. On the satellite side, the gateway requests new trunks to other gateways on the basis of traffic intensity by transmitting trunk requests to the MCS. The MCS performs trunk use supervision.

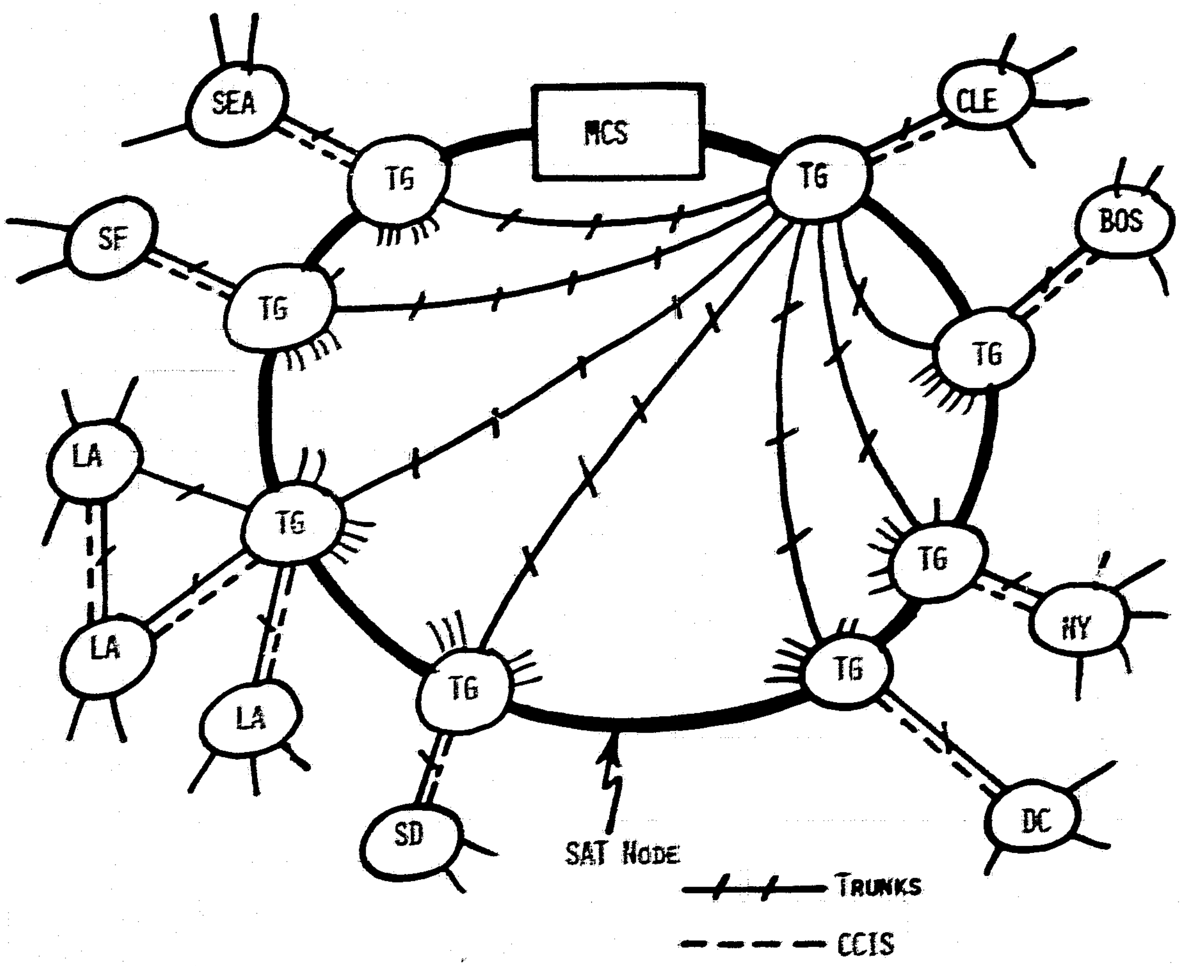

Figure 3-41. NASA Trunk System

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Between the gateways, the trunks are not removed on a call-by-call basis in contrast with the SPADE system. For example, during the East-Busy period, a number of trunks would appear to be fixed-assigned to routes in the East with heavy traffic. Such a "trunk latency" strategy would help to maintain the fast call setup time characteristic of CCIS.

4. CPS NETWORK CONTROL ARCHITECTURE

4.1 ON-BOARD BASEBAND PROCESSING

The concept of on-board baseband processing which accommodates scanning beams is shown in Figure 4-1. Each dwell area in a scanning beam sector is given an epoch in the frame to transmit or receive TDMA bursts. The duration of the epoch is dynamically allocated (demand assigned) based on the amount of station traffic in the dwell area. During a transmit epoch, a station transmits one burst composed of a number of traffic channels with various destination stations. In Figure 4-1, the burst from CPS station 1 contains traffic channels to CPS stations 4 and 6, which are located in different dwell areas. The transmitted bursts are demodulated and buffered on the satellite, and traffic channels are reassembled according to the destination dwell areas to form down-link bursts. At the proper down-beam scan period, a multiplexed traffic burst is modulated and transmitted to the designated dwell area. Each earth station in the dwell area demodulates the burst, demultiplexes the traffic channels, and extracts only the desired channels, which are routed to the respective terrestrial data ports.

On-board baseband processing involves two essential ingredients:

a. baseband switch structure and
b. baseband switch control.

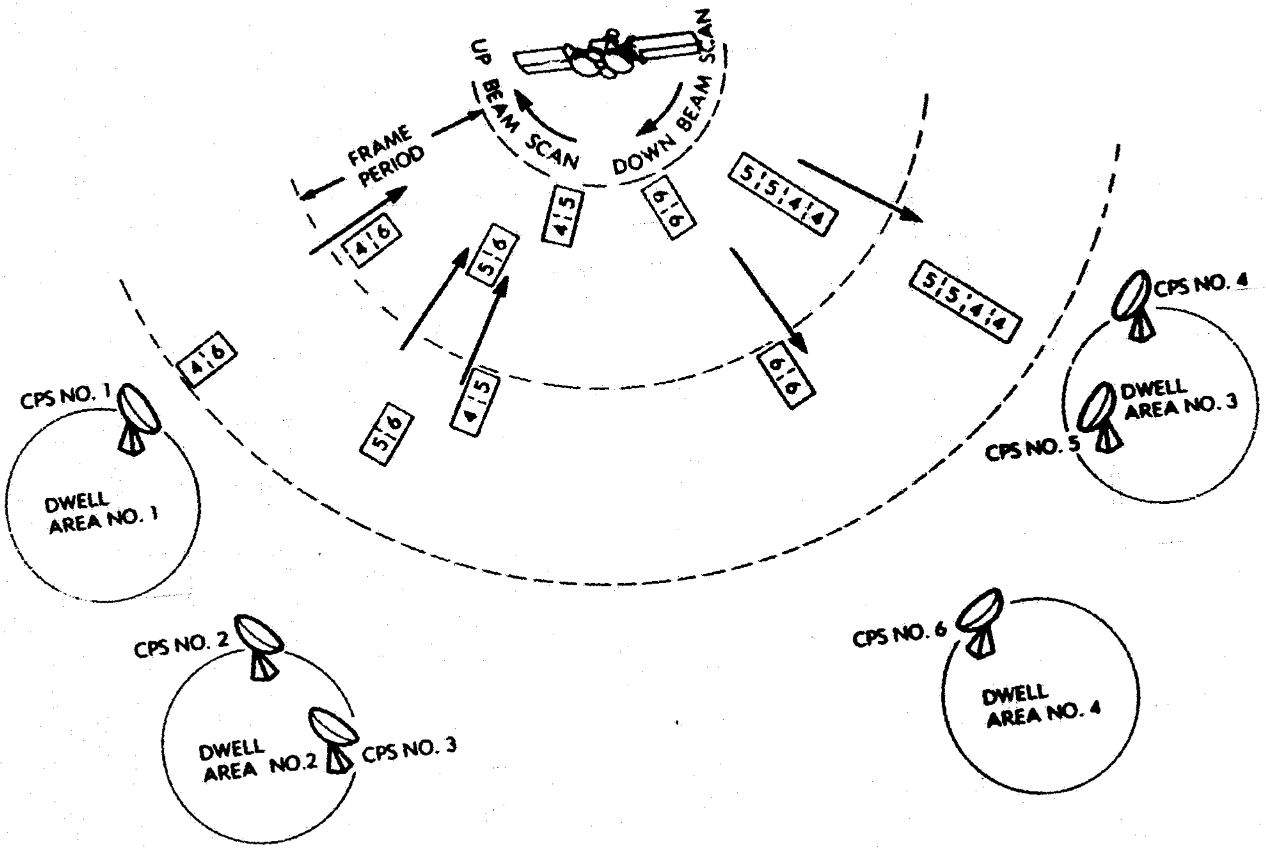

Figure 4-1. On-Board Baseband Processing With Scanning Beams

The on-board switch structure presented in the following uses the principle of time-slot switching which is widely found in time-slot interchange (TSI) telephone exchanges with stored-program control (SPC). This section presents a candidate switch structure based on this principle.

4.1.1 TRAFFIC ROUTES

The traffic routes between the scanned sector-beam pairs and the on-board time-slot switch are shown in Figure 4-2. Signal "US1" is the baseband traffic in the Up-Sector No. 1 beam after the preamble and O/W information have been stripped from the Up-Sector No. 1 bursts. Signal "DS2" is the baseband traffic destined for the Down-Sector No. 2 beam prior to insertion of the preamble, FEC and scrambling.

4.1.2 TIME-SLOT SWITCH STRUCTURE

The structure of the time-slot switch is illustrated in Figure 4-3. It is called a ping-pong slot switch because of the alternation of the READ/WRITE cycles between the two sets of RAMs. This ping-pong memory configuration is adopted because the ordinary large-scale RAM structure does not allow simultaneous reading and writing of the RAM data; the single address on the RAM address bus is either a READ or a WRITE address but not both. The ping-pong operation shown in Figure 4-3 is to write up-link frame N into one set of RAMs while the down-links are simultaneously reading the previous frame N - 1 from the other RAM set. The resulting 1-ms delay produced by the baseband switch is a

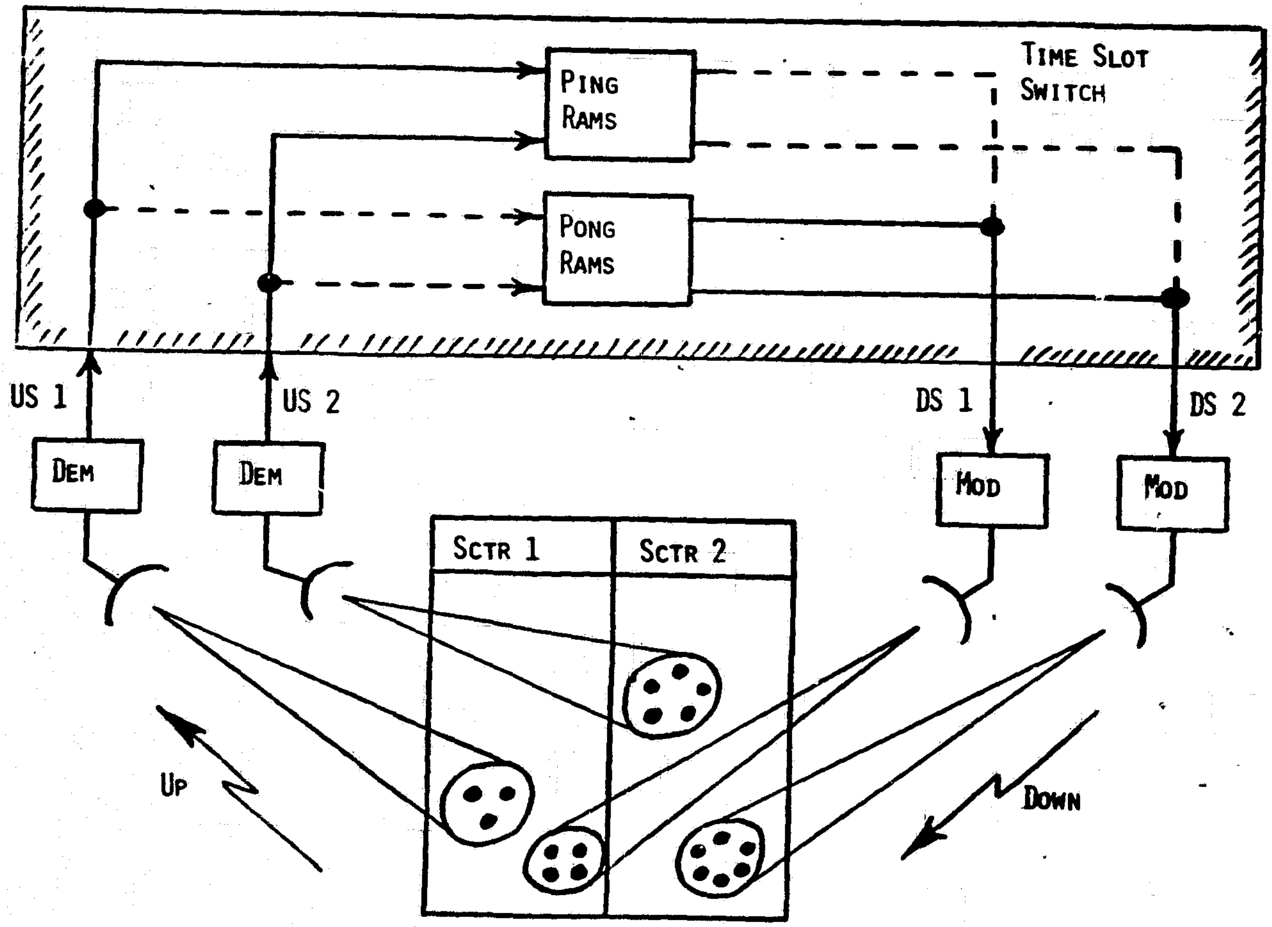

Figure 4-2. Traffic Routes and Time-Slot Switch

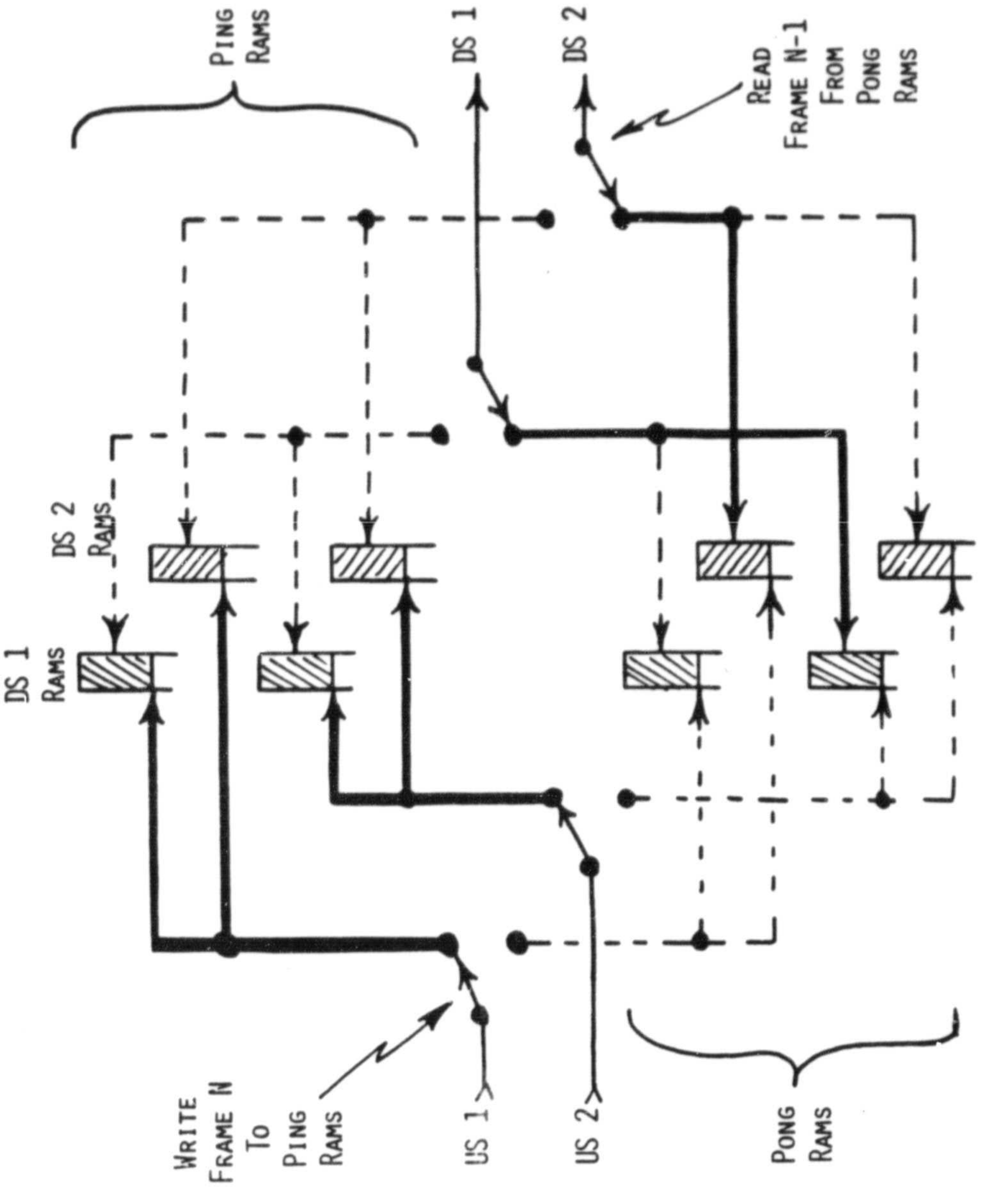

Figure 4-3. Ping-Pong Time Slot Switch

negligible addition to the up/down roundtrip satellite delay; however, the ping-pong principle improves ease of RAM access considerably. This distinction divides the RAMs into an upper (Ping) set of four RAMs and a lower (Pong) set of four RAMs.

With respect to the vertical dimension, two distinct data sinks must also be available for the up-link traffic because bursts arrive simultaneously from two earth sectors. In fact, for multi-up-link carrier operation (i.e., 4 x 32 Mbit/s), baseband data are received simultaneously from four distinct demodulators associated with a single up-sector beam.

In the horizontal dimension, the RAMs are divided with respect to the destination down sectors (i.e., DS1 RAMs and DS2 RAMs). This is necessary to allow simultaneous reading of DS1 and DS2 information originating from the same up-sector. The problem is illustrated in Figure 4-4 where the up-link traffic is written into a single RAM; the two separate down-links cannot simultaneously fetch different blocks originating in the same up-sector. Clearly, such a design would impose a severe constraint on up-link traffic allocation, which is typical of on-board switching without on-board storage.

4.1.3 UP-LINK WRITE OPERATION

Complexity is reduced by using common circuits wherever possible. This is illustrated for the WRITE operation in Figure 4-5. Such commonality is desirable, for example, if the switch is to be expanded later to accommodate more than the current two earth-coverage sectors.

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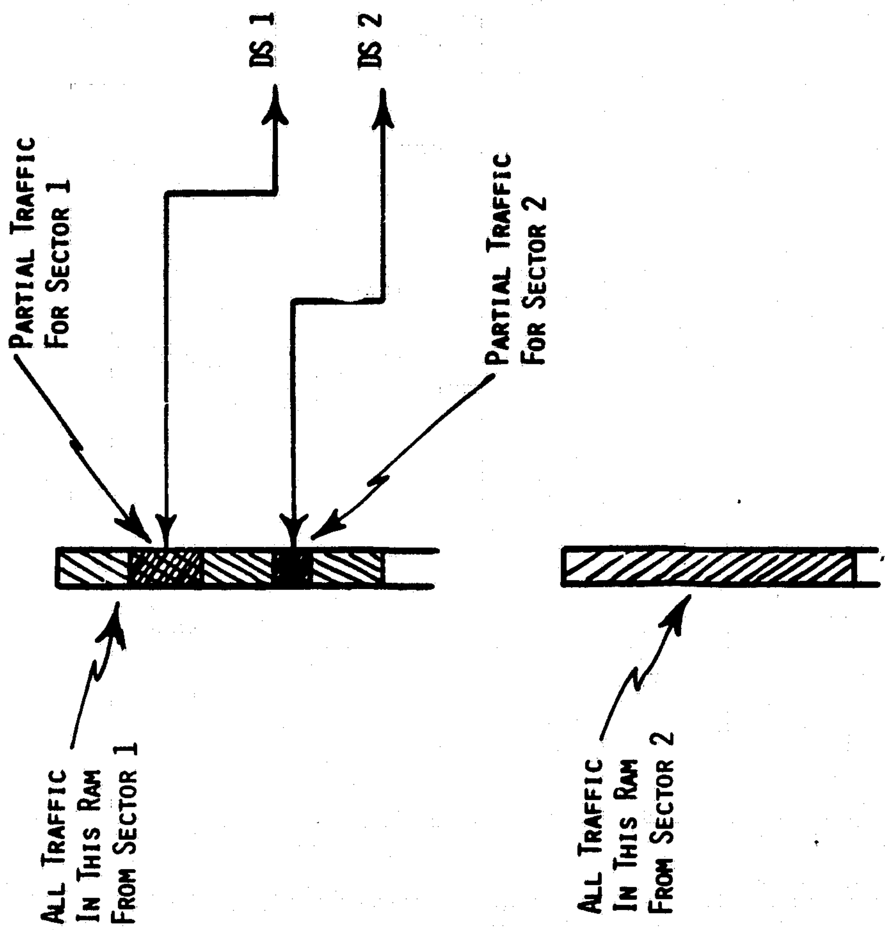

Figure 4-4. Single Per Up-Link RAM Operation

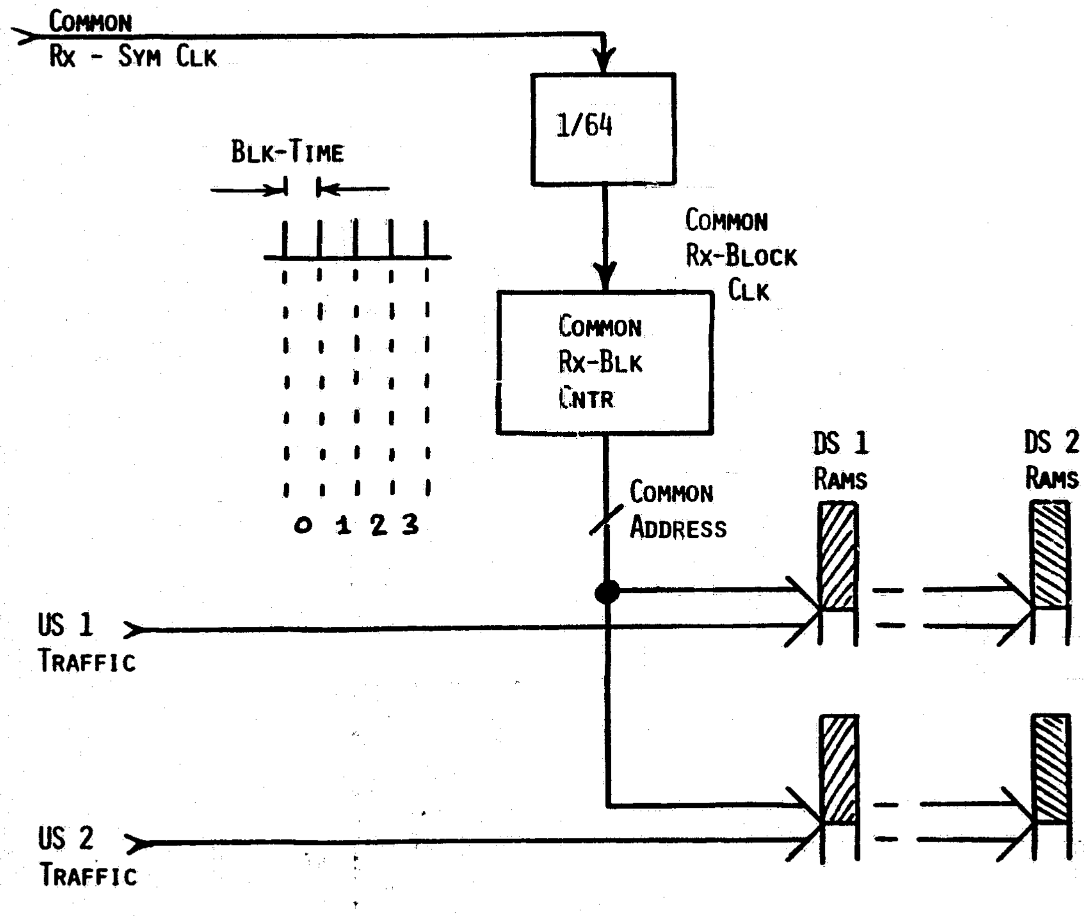

Figure 4-5. Common Receive-Write Operation

4.1.4 SYNCHRONOUS SWITCH OPERATION

The circuit commonality in Figure 4-5 implies that the switch is operated in a fully synchronous manner. The necessary synchronization of the up-link receive data from different up-link beams is achieved by the elastic buffers shown in Figure 4-6. The WRITE rates to these buffers are slightly different, but there is only one READ rate, controlled by the on-board clock. The stippled lines inside these buffers suggest the memory-page segmentation necessary to allow simultaneous READ/WRITE access. The READ/WRITE pointers of these buffers are set to 180° phase difference at the start-of-burst. These are small memories, depending on up-link clock stability and Doppler shift.

4.1.5 DOWN-LINK READ OPERATION

A simplified view of RAM content and READ access is given in Figure 4-7, which shows how a down-link can read data from any up-sector in an unrestricted random manner. The figure also illustrates that this time-slot switch is non-blocking.

4.1.6 BROADCAST DISTRIBUTION

Figure 4-7 also shows how broadcast information (video, speech, or data) is handled in a straightforward manner. For example, the DS1 down-link may access the broadcast information with complete destination flexibility: any number of broadcast READs may be made at any time during the down-link frame.

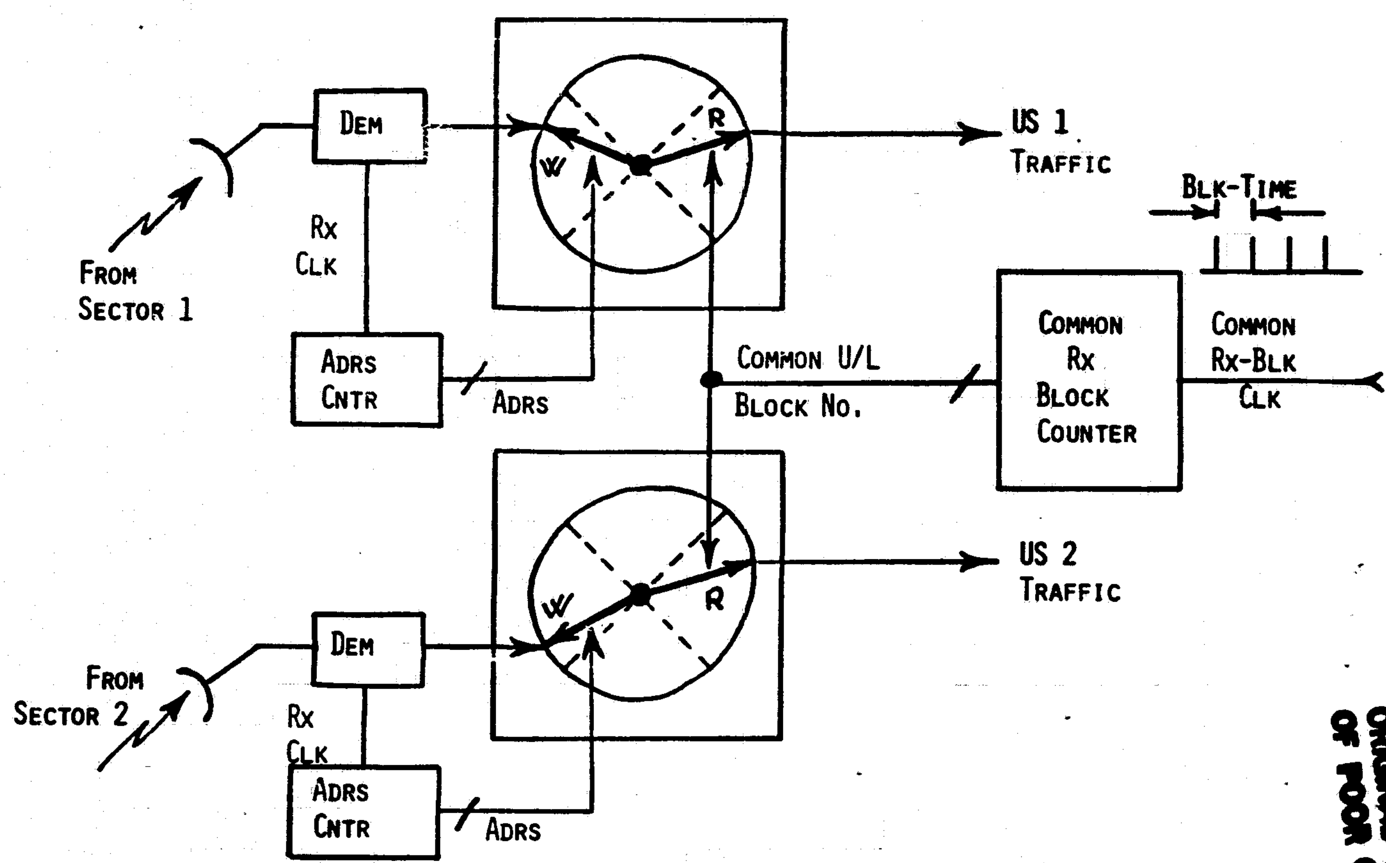

Figure 4-6. Elastic Receive Buffer Operation

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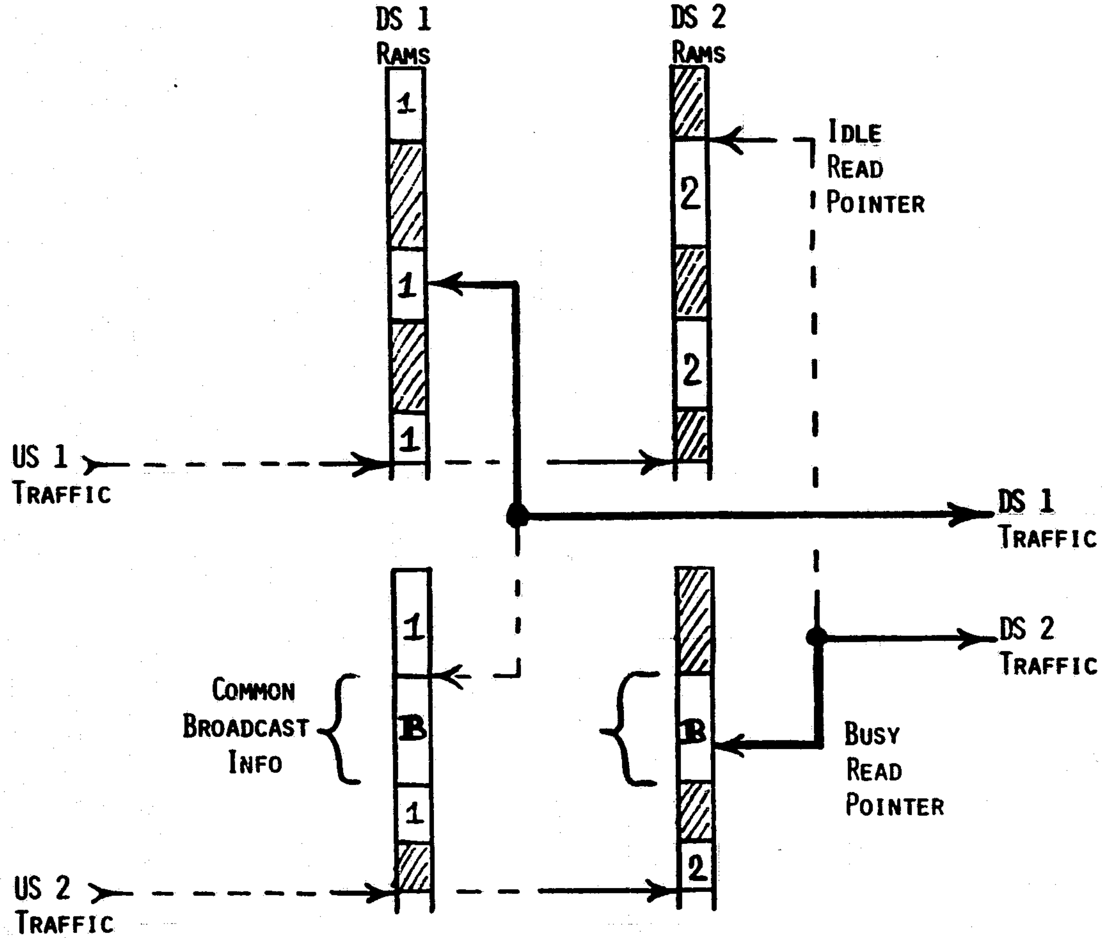

Figure 4-7. Down-Link Read Access

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4.1.7 DOWN-LINK READ SEQUENCE

Destination-specific time-slot switching is achieved by means of the READ sequence in Figure 4-8, which shows the contents in the DS2 RAMs with respect to both origin and destination. The figure presumes a typical geographic distribution exemplified in Figure 4-9. Columns 2 and 4 in Figure 4-8 list the originating and destination station connectivity. On the right is the desired READ sequence which will assemble the traffic for the individual dwell areas of the scanned down-link beam for Down-Sector 2.

4.1.8 DOWN-LINK MONO-BURSTS

The traffic distribution of the two mono-bursts for Down-Sector 2, assuming the DS2 RAM content in Figure 4-8, is shown in Figure 4-10. They are called mono-bursts because there is only one burst per down-link dwell area. In this implementation, no attempt is made to assemble the traffic for a particular destination station into one contiguous part of the mono-burst.

4.2 BASEBAND PROCESSOR CONTROL

The on-board time-slot switch is controlled by a set of down-link READ maps generated at the MCS station. These maps are first extracted from the burst time plan (BTP) by the MCS Traffic Executive (MCS/TRAFEX) and then transmitted to the on-board RAMs via the orderwire.

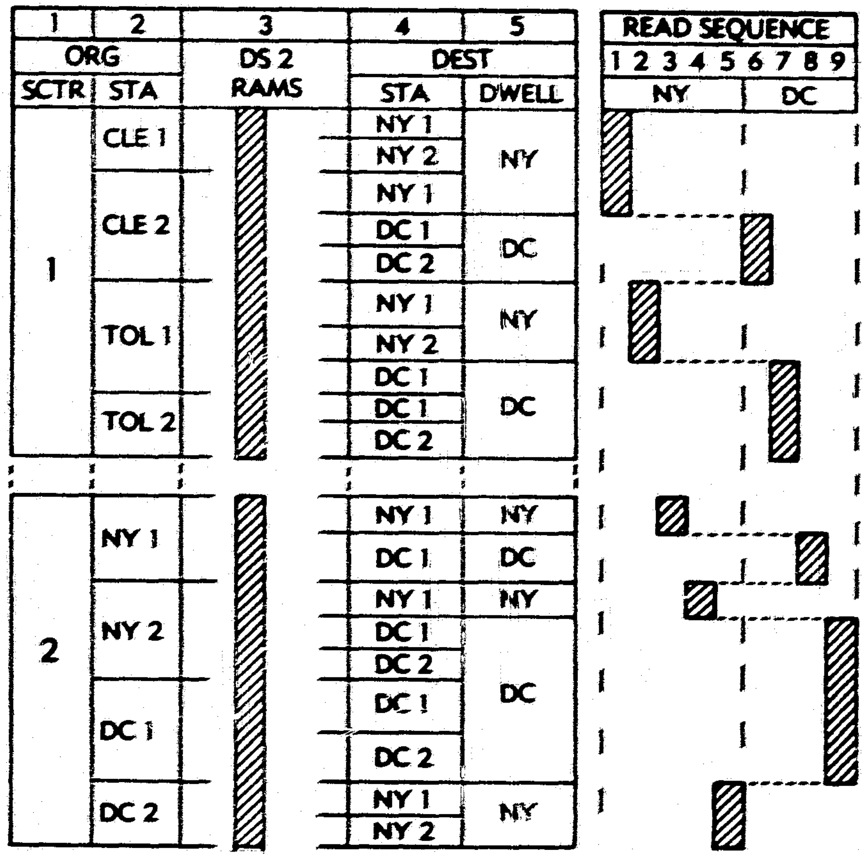

Figure 4-8. Dwell-Area-Specific Read

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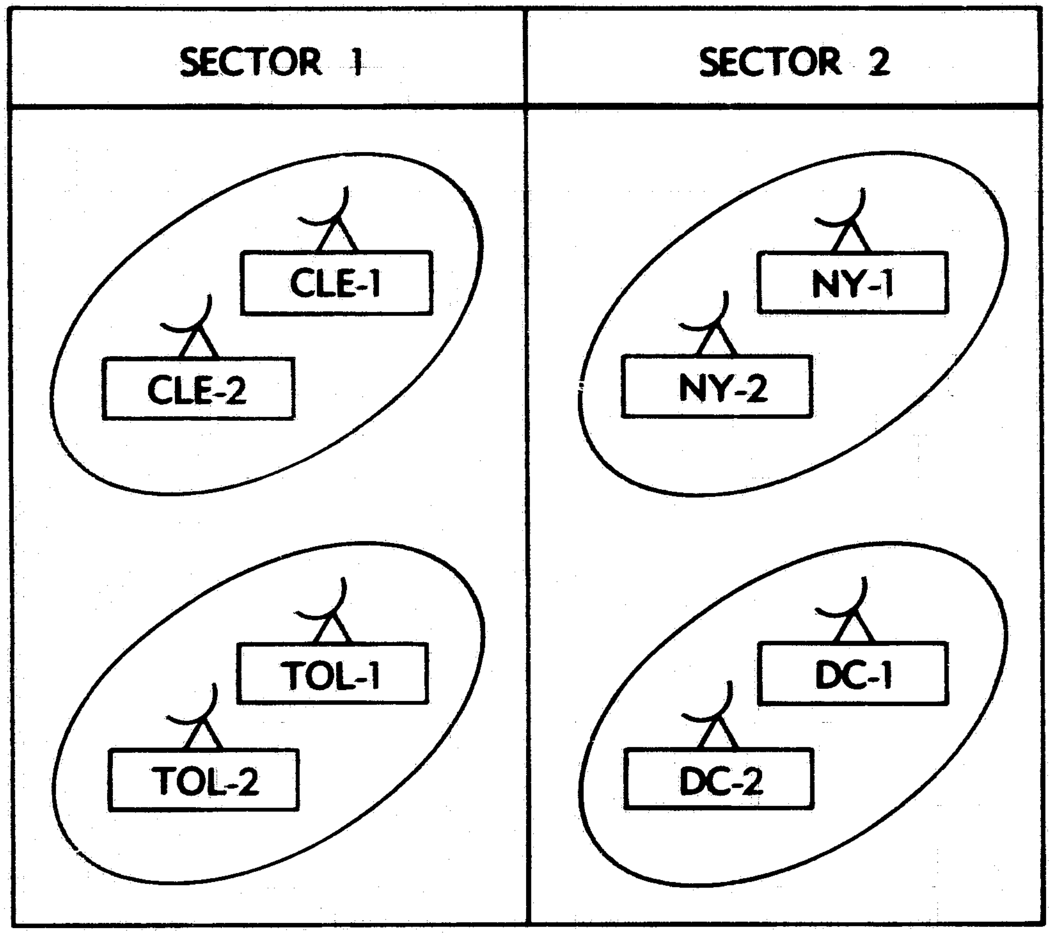

Figure 4-9. Station Distribution

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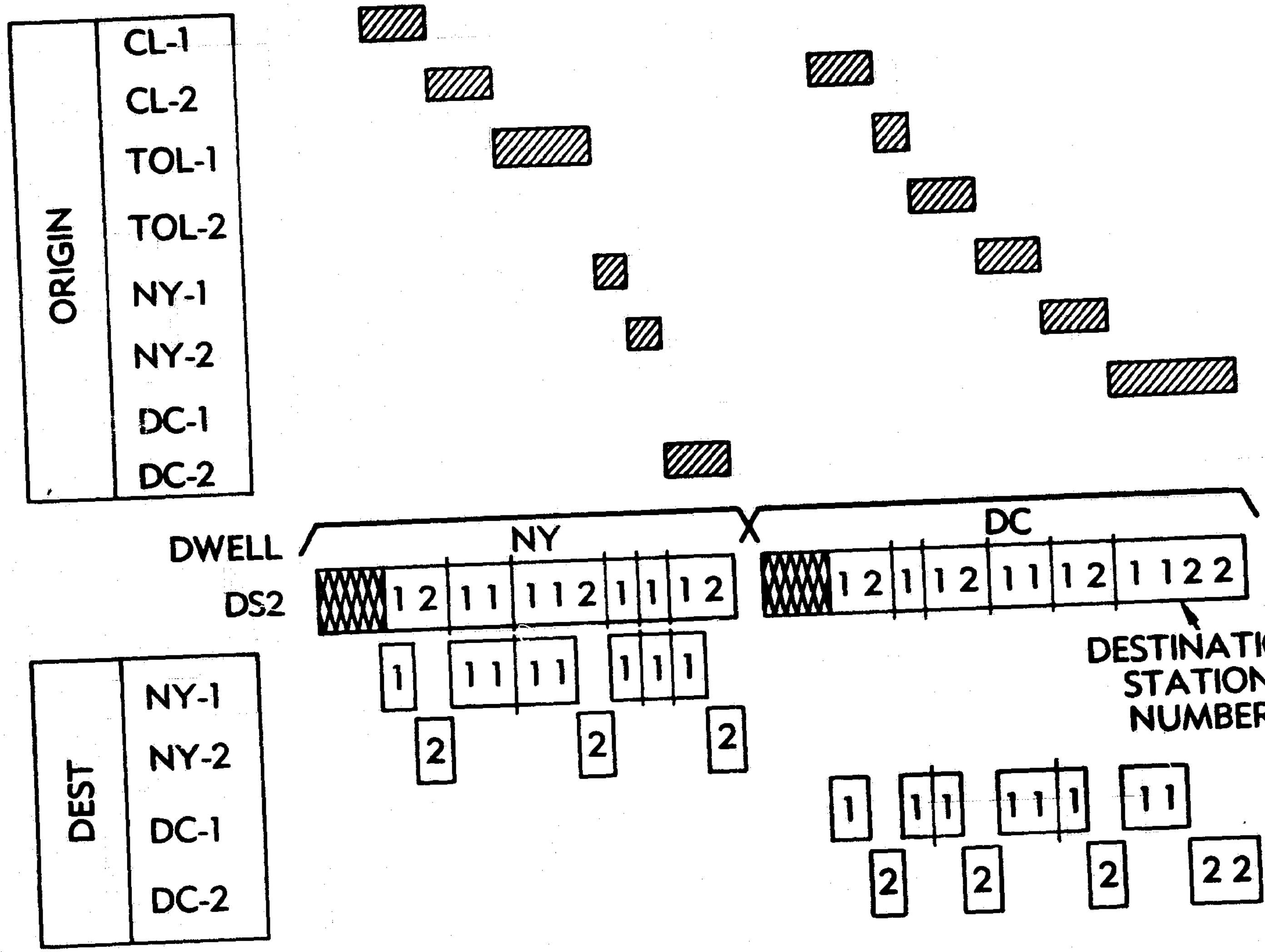

Figure 4-10. Down-Link Mono-Burst Constitution

4.2.1 TIME-SLOT READ MAPS

A unique READ map (Figure 4-11) is asssociated with each down-link. The active READ map controls the fast block-to-destination selection at the block-switching rate. The passive READ map serves as a standby depository for the next down-link map transmitted from the MCS station. Once loaded, the passive READ maps are available for fast switchover without loss of traffic. The switchover is controlled by a frame countdown protocol.

4.2.2 DOWN-LINK READ CONTROL MECHANISM

The READ circuitry is outlined in Figure 4-12. The READ map provides a straightforward table translation from down-link transmit block number to RAM block address. The basic transmission unit is the block (32 symbols). Figure 4-12 shows that each RAM block address has an associated 'ORG' tag bit that identifies which of the two RAMs is to be accessed. This is further detailed in Figure 4-13, which also indicates how both down-links share a common Tx block-number. In sub-multiplexing over a multi-frame period, the Tx block number indicates the frame number.

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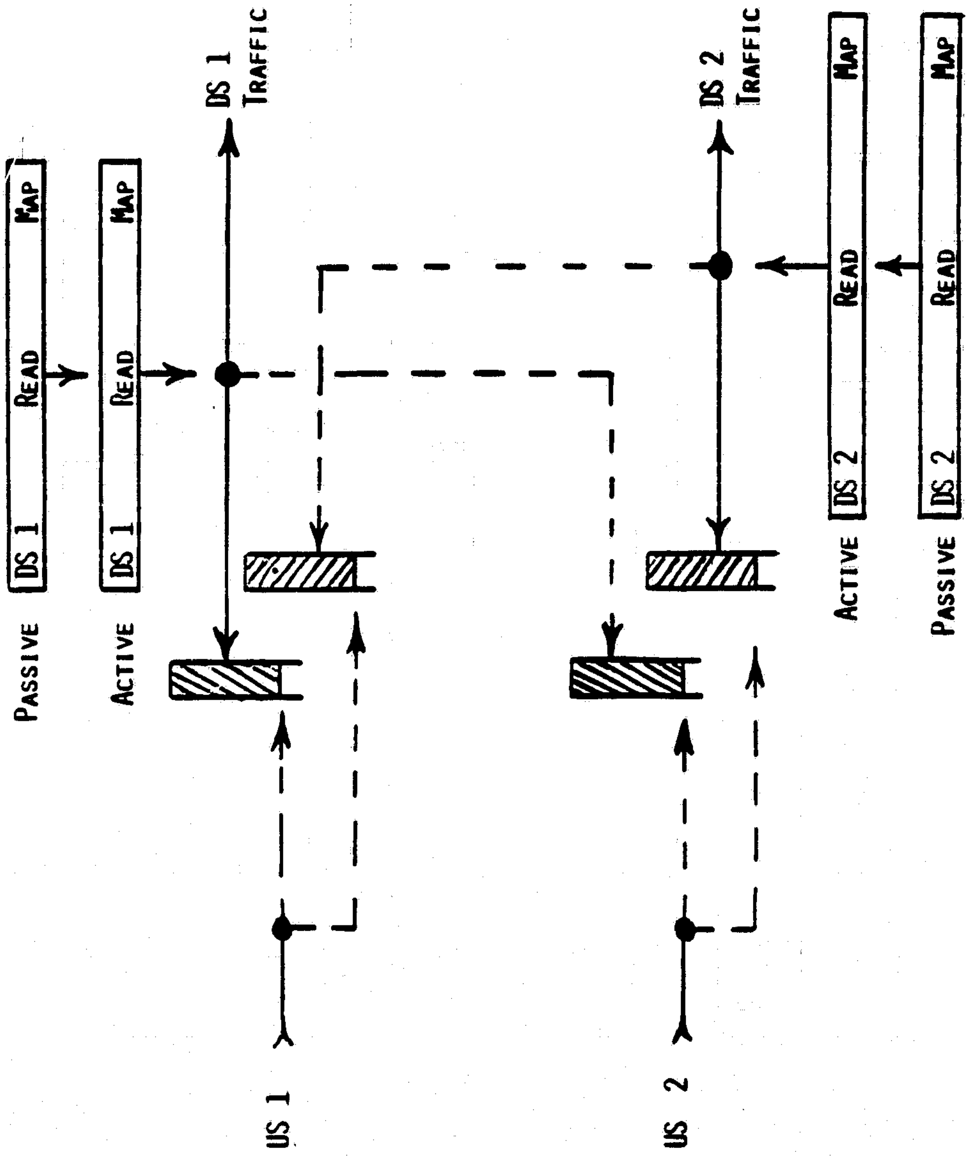

Figure 4-11. Time-Slot Read Maps

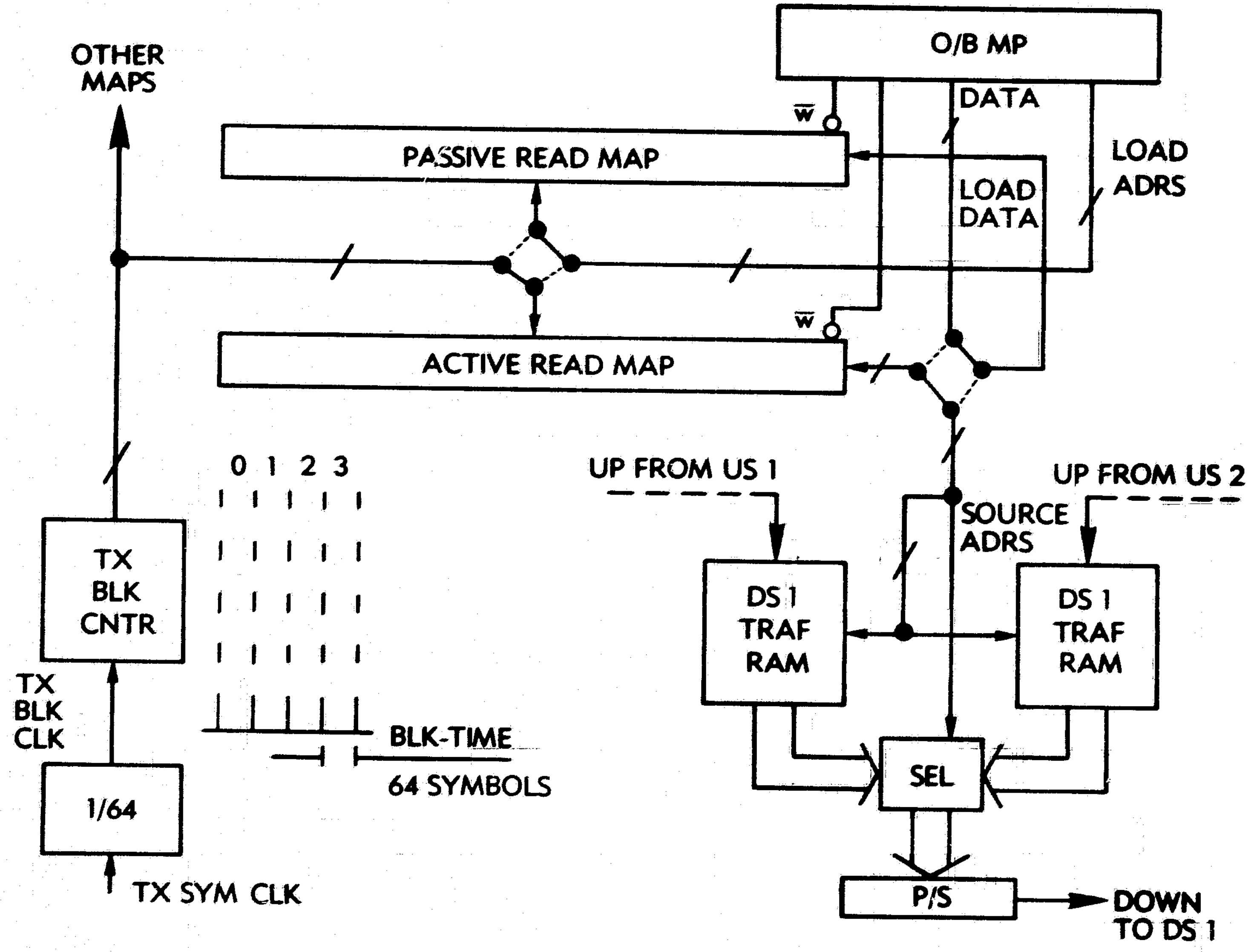

Figure 4-12. Dest-Dwell Read Control

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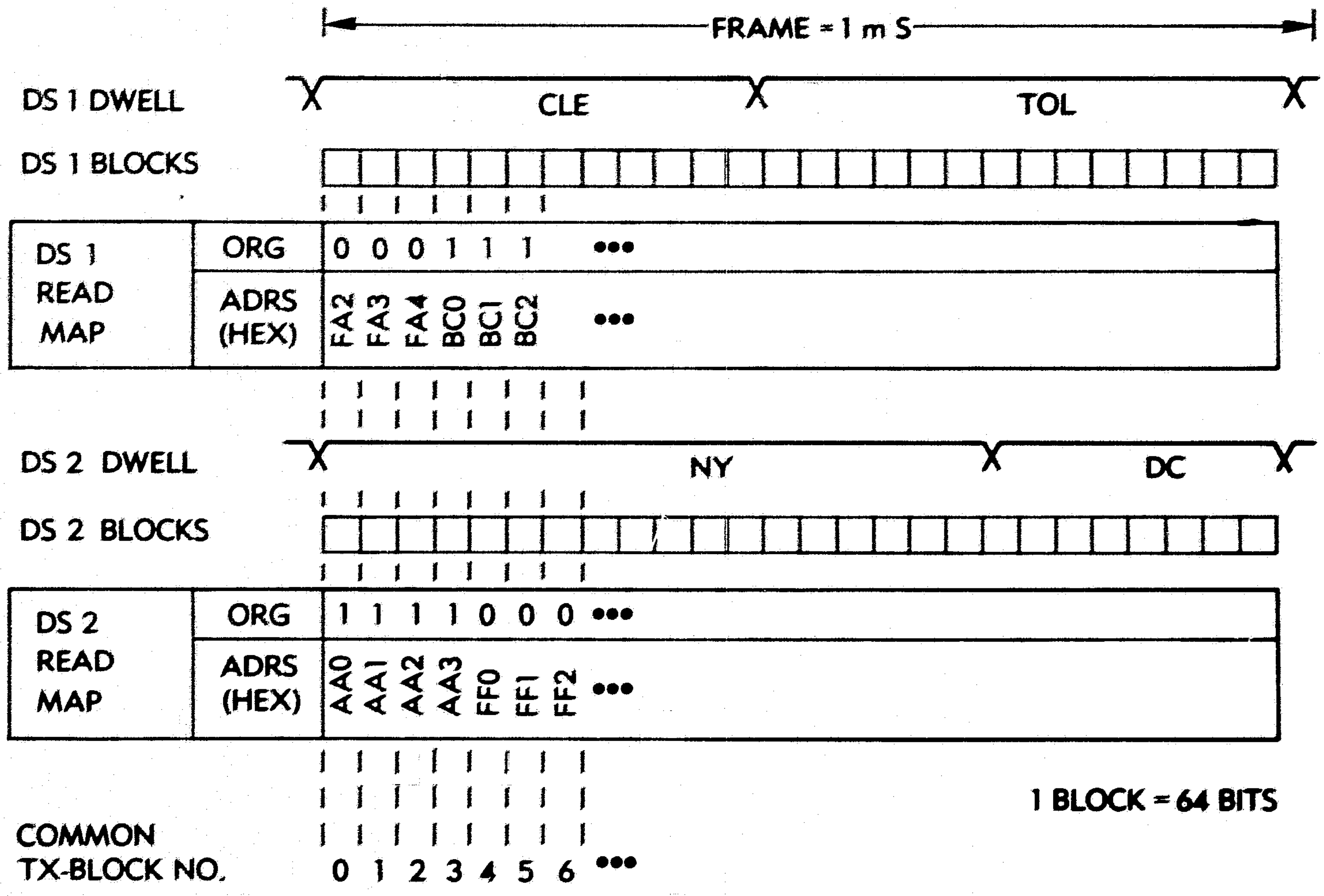

Figure 4-13. Down-Link Read Maps

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4.3 FRAME AND CONTROL FRAME STRUCTURES

4.3.1 FRAME STRUCTURES

The up-link frame structure is shown in Figure 4-14a. The frame is divided into a number of time segments, each assigned to a particular dwell area. Each dwell segment contains orderwire burst slots that are time-shared by the CPS stations in that area, traffic bursts carrying station traffic, and a control burst slot. The control burst corresponds to the reference burst in the trunk network and transports order-wire data to the on-board baseband processor and network stations; however, it is not used as a receive timing source by the CPS stations. The order-wire data are error-protected with FEC coding, CRC coding, and duplicated data transmissions. Various orderwire data fields are demultiplexed and reformatted on the satellite and used to control the baseband processor, or retransmitted to the proper down-link beams in the CPS orderwire field for station control. A station orderwire burst contains alarm/status data and channel request information and is multiplexed with other station order-wire channels on the satellite and transmitted to the MCS in the MCS orderwire channel. One orderwire burst slot is sufficient for the experimental system.

The down-link frame consists of several area bursts, each containing multiplexed orderwire data (CPS orderwire) and traffic channels to CPS stations (Figure 4-14b). The MCS area burst has an additional orderwire field (MCS orderwire) for the alarm and status data of the baseband processor and network stations. The down-link orderwire structure is detailed in Figure 4-15. The MCS orderwire comprises baseband processor

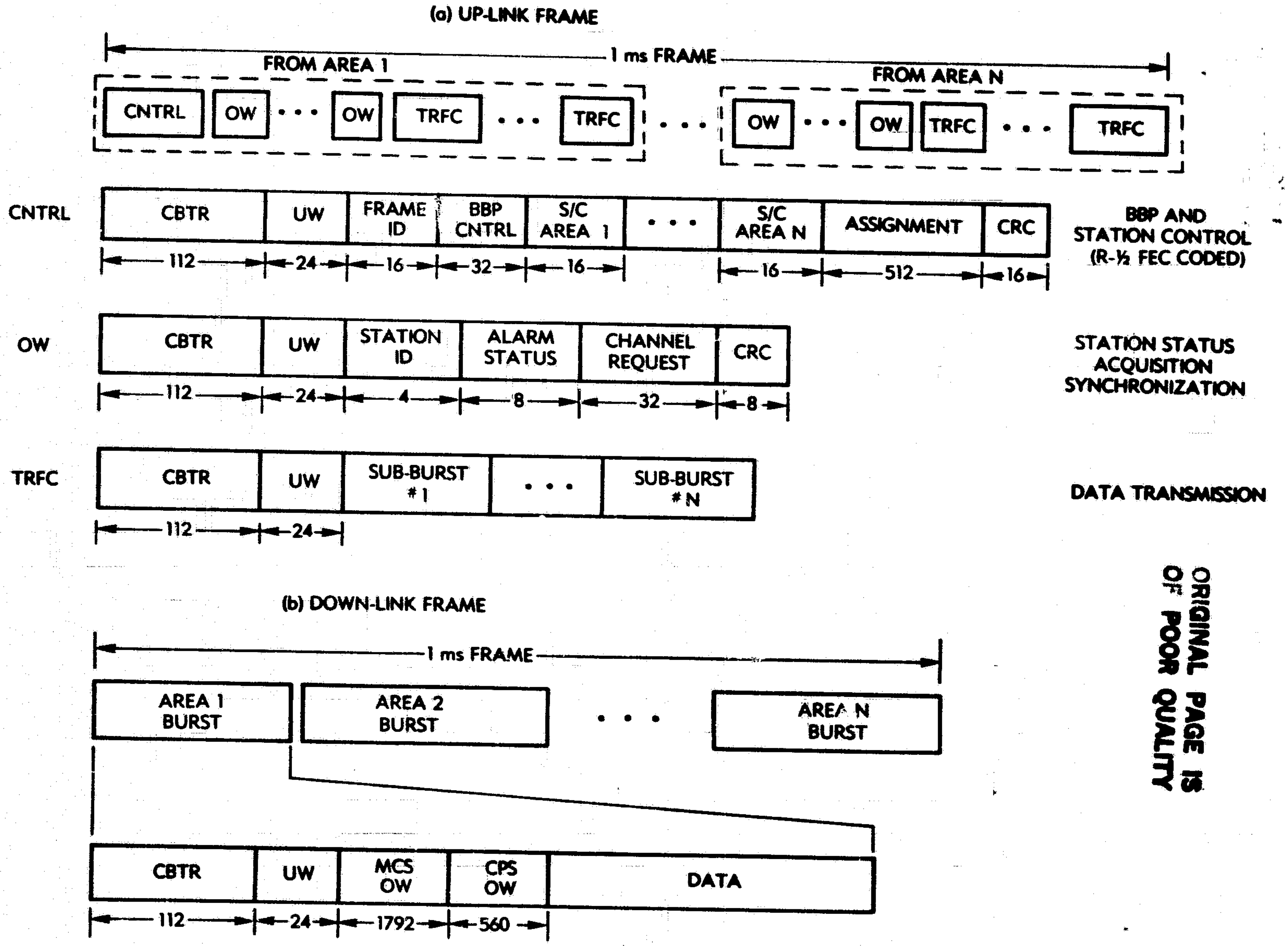

Figure 4-14. Frame Structure

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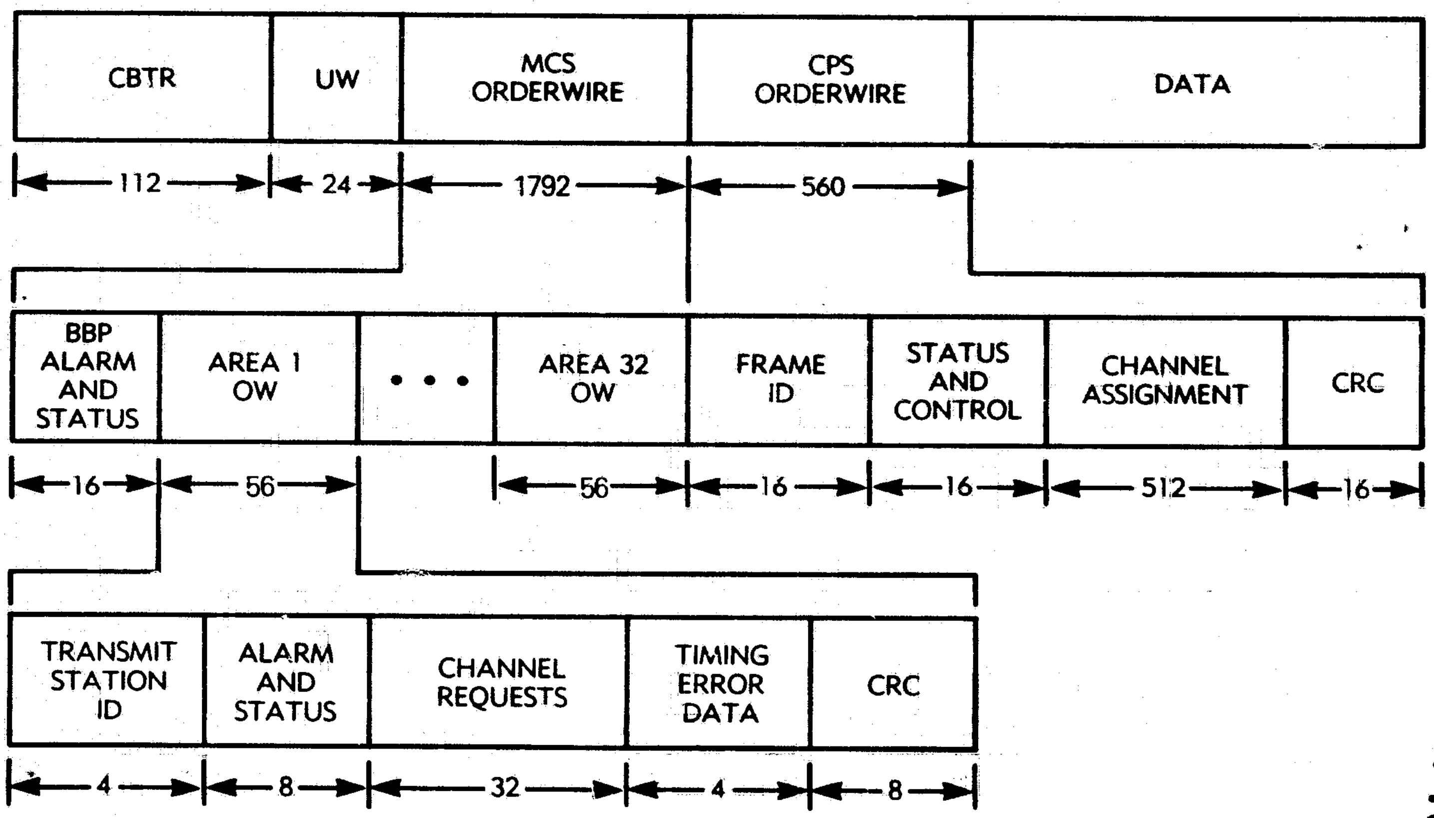


Figure 4-15. Down-link Orderwire Channel Structure

alarm and status data and station orderwires from 32 dwell areas. Each area orderwire contains CPS orderwire data and on-board measurement data on the transmit synchronization error. The CPS orderwire field is extracted from the control burst orderwire and addressed to the CPS stations in the designated dwell area.

The frame structure given above can accommodate two scanning beams, 16 dwell areas per beam, 32 CPS stations per dwell area, and a total of 128 stations in the network. This basic frame design can easily be expanded to a larger earth station network.

4.3.2 CONTROL FRAME STRUCTURE

The basic control architecture of the CPS network, which is similar to that of the trunk network, is summarized in Table 4-1. For the CPS network, one major exception is a shorter channel reconfiguration period, i.e., 1.024 s vs 65.536 s. The CPS system employs rate one-half FEC coding for rain fade control. The adaptive FEC technique requires rapid channel reconfiguration before the rain fade affects network operation. According to COMSTAR 30-GHz Beacon experiments, the maximum uplink fade rate is 1 dB/s, and the 1-second reconfiguration period results in about 3.5-dB link degradation between fade detection and subsequent FEC application. The clear sky link margin without coding must be at least 3.5 dB above the minimum system requirement to accommodate the adaptive FEC control.

Table 4-1. Control Frame Composition

	Number of Assignment Frames	Number of Multi-frames	Number of Frames	Functions
Control Frame	4	32	1024	Duplicated Assignment Maps Assignment Execution Transmit Timing Correction Station Control
Assignment Frame		8	256	Channel Assignment Map
Multiframe			32	Transmit Timing Measurement Orderwire Transmission

Error probability calculations of various control burst orderwire fields are given in Table 4-2. The CPS network operates quite reliably at the channel BER of 10^{-3}.

4.4 ACQUISITION AND SYNCHRONIZATION

4.4.1 ACQUISITION AND SYNCHRONIZATION PROCEDURE

A CPS station begins the initial acquisition process by transmitting an acquisition orderwire burst based on the satellite range data. The timing error is measured on board and sent to the MCS via the MCS orderwire channel, which in turn retransmits it to the acquiring earth station. The station transmit clock is subsequently adjusted, and the orderwire bursts are

Table 4-2. Error Probability of Control Burst Orderwire*

Channel BER	Decoder Output BER	Frame ID Error Probability	BBP Data Error Probability	S/C Field Error Probability	Assignment Error Probability
10^{-2}	1.12×10^{-4}	1.1×10^{-1}	1.0	1.5×10^{-1}	1.0
10^{-3}	1.12×10^{-7}	1.2×10^{-4}	8.9×10^{-7}	9.0×10^{-13}	1.1×10^{-7}

*The control burst orderwire is FEC encoded using the (16,8) shortened quadratic residue code given in Section 3.

transmitted with new timing. Repeating this feedback error correction process reduces the timing error to within ±2 symbols. The MCS then sends a command to the BBP to narrow its unique word aperture width from 86 to 8 symbols and simultaneously instructs the CPS station to transmit traffic bursts. The acquisition and synchronization process is shown in Figure 4-16.

4.4.2 ON-BOARD TIMING ERROR MEASUREMENTS

Acquisition and synchronization error is measured on the satellite in the orderwire burst slot. The timing relationship of the burst slot and aperture window is shown in Figure 4-17. The acquisition burst slot length is the sum of the satellite ranging accuracy of ±200 m (or ±667 ns) and the orderwire burst length of 188 symbols. This is equivalent to 274 symbols (or 4.28 μs) at 128 Mbit/s and 210 symbols (or 13.08 μs) at 32 Mbit/s. During the acquisition process, the BBP opens a wide aperture of 86 symbols (at 128 Mbit/s) or 24 symbols (at 32 Mbit/s) for orderwire UW detection. When the timing error is reduced to ±2 symbols, the aperture width is narrowed to 8 symbols to avoid UW false detection.

4.4.3 SYNCHRONIZATION PARAMETERS

Synchronization parameters for the CPS network are listed in Table 4-3. The station orderwire burst requires 1.333 μs of guard time due to the satellite range measurement error, and traffic bursts transmitted from the same dwell area are allocated 8 symbols of guard time to absorb ±2 symbols of

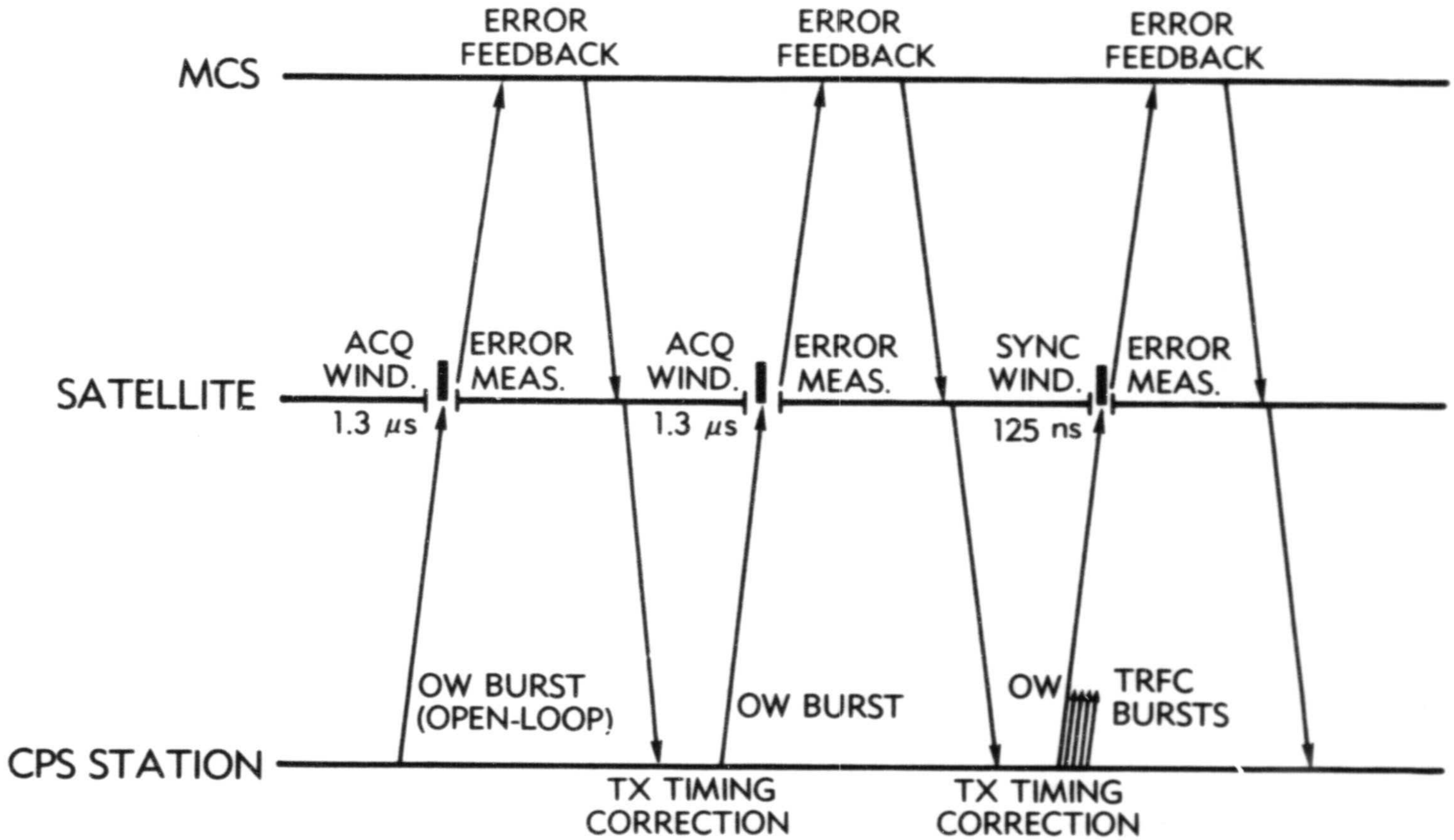
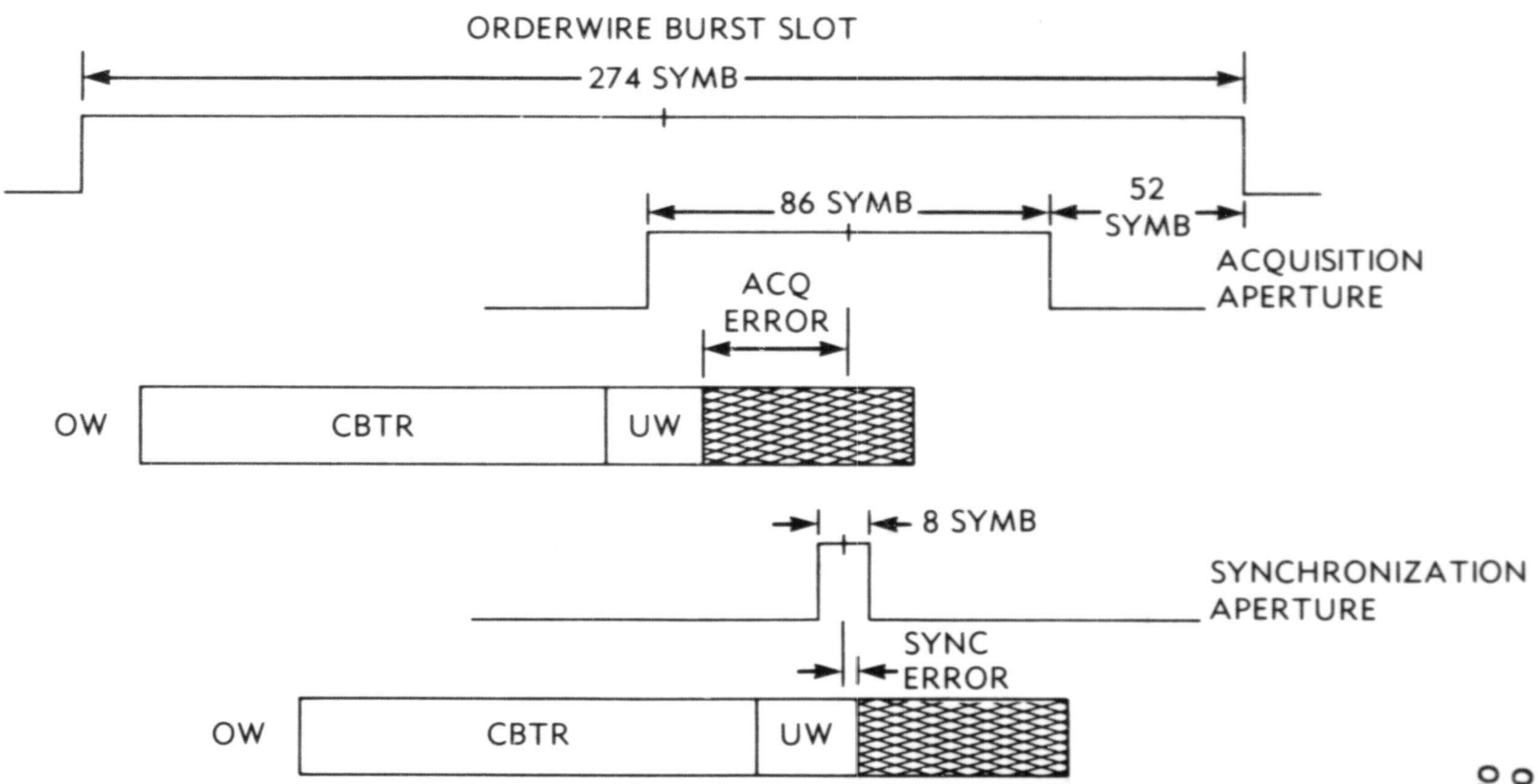


Figure 4-16. Acquisition and Synchronization Procedure



• THE ILLUSTRATION IS FOR THE 128-Mbit/s UP-LINK BURST RATE

Figure 4-17. On-Board Timing Error Measurements timing error. In addition, an on-board beam switching time of 1 μs is included as a guard time between successive dwell area illumination.

Table 4-3. Summary of Synchronization Parameters

	Acquisition Accuracy	Synchronization Accuracy	Guard Time
Orderwire Burst	±667 ns	±2 symbols	1.333 μs
Traffic Burst	N/A	±2 symbols	8 symbols
Area Burst (down-link)	N/A	N/A	1 μs

4.5 ORDERWIRE TRANSMISSION

CPS network control requires an orderwire system for aquisition/synchronization, fade detection and adaptive FEC control, and network entry. This requirement is satisfied by reserving several time slots at the beginning of each frame for up-link orderwire bursts. These slots are shared among the CPS terminals on a rotating basis. Up-link MCS orderwire information, contained in the control burst that begins each frame, is collected and reformatted on board by the baseband processor and transmitted at the beginning of each area burst. The position of the orderwire data in the up-link and down-link frames is shown in Figures 4-14 and 4-15.

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4.6 CHANNEL ASSIGNMENT

4.6.1 DEMAND ASSIGNMENT

Demand assignment of channel capacity is required in the CPS network to accommodate fluctuations in terminal data throughput. The thin route traffic for which the CPS system is designed is bursty. In addition, occasional rain events impose demands for increased capacity for FEC application.

Demand assignment in the CPS network is accomplished by modifying the traffic assignment table in response to channel requests made by CPS stations via the orderwire. Assignment table transmission requires one control frame (1024 TDMA frames); thus, traffic assignment modifications can be made only once per control frame (1 s). At any given time, the MCS maintains three assignment tables: the current traffic table; the next traffic table, which is being transmitted to the CPS stations; and the update traffic table, which is being continually modified in response to CPS fading and traffic fluctuations. At any end of a control frame, the current assignment table is discarded and the update table becomes the next traffic table. Fade data are processed by the MCS, and the burst expansion requirements which are generated are treated as channel requests by the table generation algorithm. Appropriate use of allocated channels (for fade compensation or traffic expansion) is controlled by the MCS via the orderwire.

4.6.2 CHANNEL ASSIGNMENT PROCEDURE

The channel assignment procedure for the CPS network is straightforward. Since all traffic channels are buffered on the satellite, CPS traffic scheduling is the same as in a single-carrier TDMA system, and up-link and down-link channel assignments are independently accomplished for each dwell area.

The MCS creates a station traffic matrix from channel request data and condenses it to a dwell area traffic map. Transmit and receive BTPs are generated for each dwell area. There are several traffic burst slots on the up-link and only one burst on the down-link in a dwell area. The area BTPs are assembled to produce two sector BTPs. Unused channel capacity may be allocated for rain fade control and future traffic growth. An example of channel assignment is shown in Figures 4-18 and 4-19, where one traffic unit is equivalent to one 64-kbit/s channel, and one scanning beam case is illustrated.

Although there is no need for complex beam traffic scheduling, the MCS requires timing computations for the BBP channel routing controller to process individual traffic channels.

4.6.3 CHANNEL ASSIGNMENT TIMING

The channel assignment execution procedure must coordinate the processing timing of three network segments, the MCS, on-board BBP, and CPS stations, so that no data loss occurs during an assignment change. The timing skew of the on-board receive and transmit frames is normally one or two frames, depending on the BBP processing architecture, and requires proper

(a) STATION TRAFFIC MATRIX

TX \ RX		AREA 1		AREA 2			AREA 3		
		CPS_{11}	CPS_{12}	CPS_{21}	CPS_{22}	CPS_{23}	CPS_{31}	CPS_{32}	CPS_{33}
AREA 1	CPS_{11}		25			20	50		25
	CPS_{12}	20		15				10	
AREA 2	CPS_{21}					25			
	CPS_{22}		20			40			
	CPS_{23}		10		50			60	
AREA 3	CPS_{31}	120		40					
	CPS_{32}				20				180
	CPS_{33}		60				20	10	

(b) AREA BEAM TRAFFIC MAP

	AREA 1		AREA 2			AREA 3		
	CPS_{11}	CPS_{12}	CPS_{21}	CPS_{22}	CPS_{23}	CPS_{31}	CPS_{32}	CPS_{33}
TRANSMIT TRAFFIC	120	45	25	60	120	160	200	90
RECEIVE TRAFFIC	140	115	55	70	85	70	80	205

Figure 4-18. Station Traffic Matrix and Area Beam Traffic Map

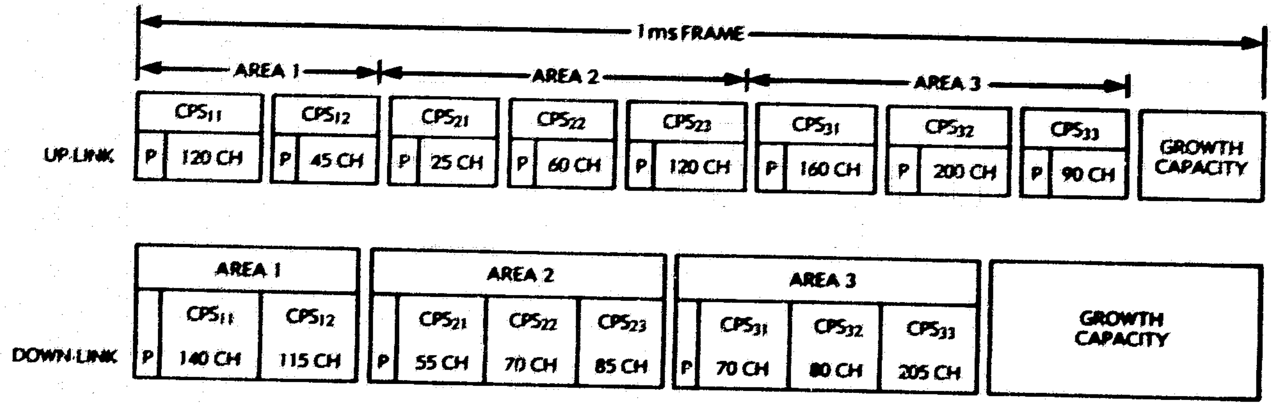

Figure 4-19. Up-Link and Down-Link Channel Assignments

timing adjustments by each CPS station processor. This is illustrated in Figure 4-20 for a 1-frame processing delay. The assignment execution command is transmitted from the MCS on the control burst and distributed on the satellite to all the CPS stations in the status/control field of the down-link orderwire channels.

4.7 FADE DETECTION

CPS signal fade detection is very similar to trunk signal fade detection, which was discussed in Subsection 3.7. Due to the on-board signal regeneration, path fades must be measured by monitoring the level of a signal which traverses a path essentially identical to that of the communications signal. This "metering signal" can be generated either on the ground or on board, and is measured at the opposite end. Each frequency will be considered separately.

For 20 GHz, two existing signals are available for fade measurement: the communications signal itself and the TT&C beacon. In addition, a pilot signal may be generated at the CPS station to monitor its power level on board. Measurement of the communications signal power can be accomplished using an AGC type circuit which has been optimized for speed of response. This approach is shown in Figure 4-21. Although this requires measurement of a burst signal, the minimum down-link burst duration is approximately 11 μs, which is well within the capabilities of this technique [28]. Measurement of the TT&C beacon power level is also feasible and is slightly simpler due to the continuous nature of this signal. In addition, it will provide significantly greater operating range due to its relatively narrowband

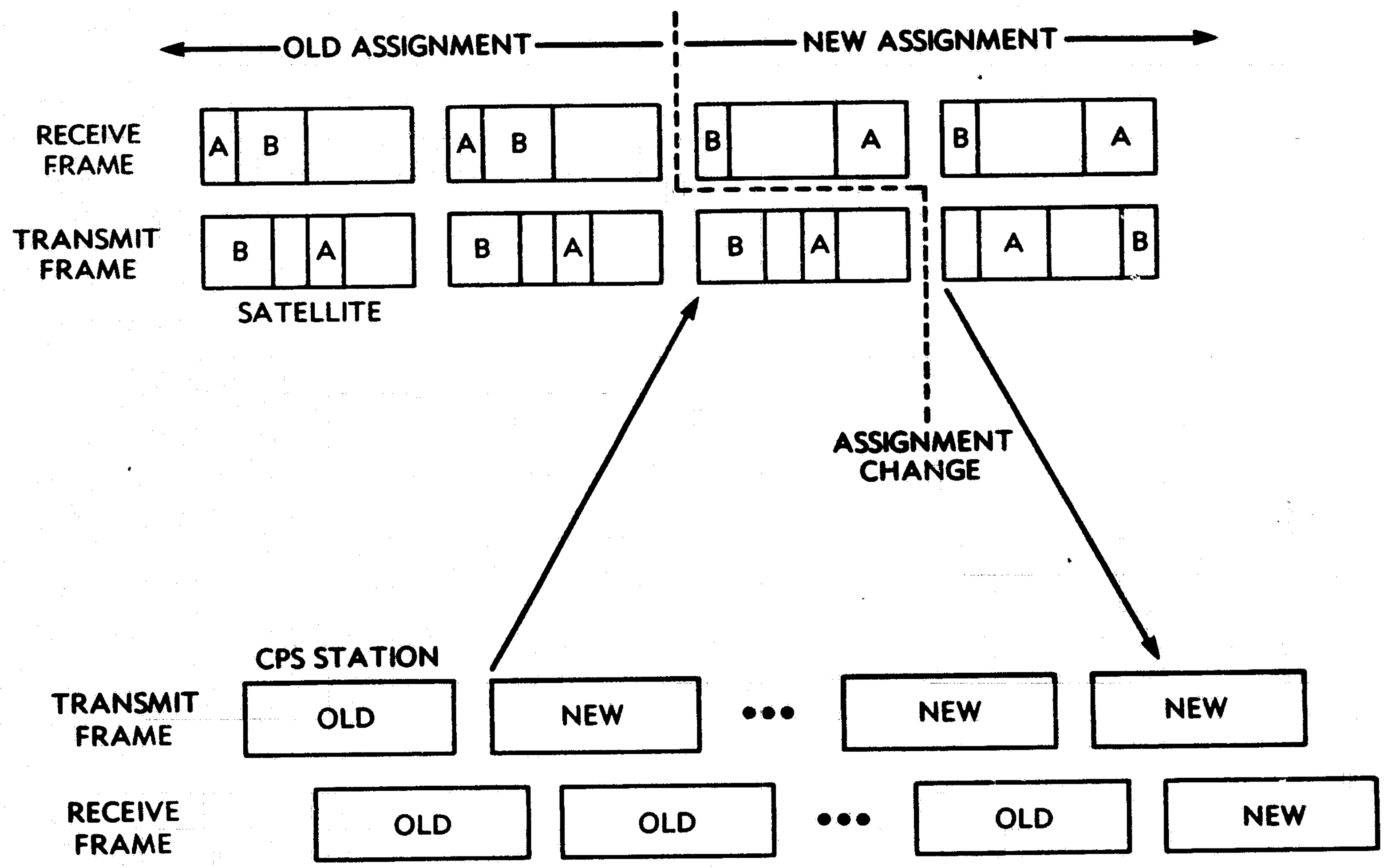

Figure 4-20. Channel Assignment Timing

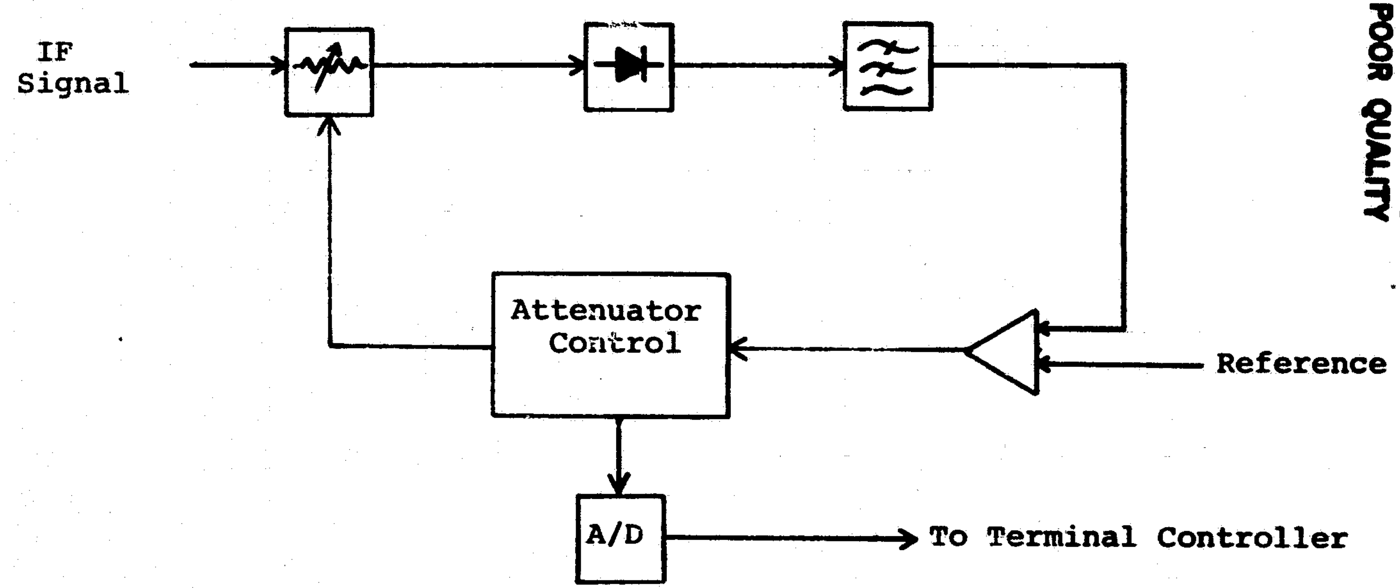

Figure 4-21. AGC Type Power Measurement Circuit

nature. Operating at a C/N of roughly 20 dB, a carrier measurement system has less than 15 dB of useful operating range. Table 4-4 shows a link budget for a hypothetical 20-GHz beacon of 1-W output power. The C/N of 51 dB would provide 30 dB greater operating range.

Table 4-4. 20-GHz Beacon Link Budget - CPS

Beacon Power	0 dBW
Transmit Antenna Gain	30 dB
e.i.r.p.	30 dBW
Path Loss	-210 dB
Receive Antenna Gain (3 m)	53 dB
Receive Signal Power	-127 dBW
System Temperature, T	28 dB
C/kT (K = 228.6 dB/°K)	74 dB
PLL Bandwidth	23 dB-Hz
C/N	51 dB

Use of a 20-GHz up-link pilot requires additional satellite hardware and involves complex filtering to avoid overloading the satellite LNA as discussed in Subsection 3.7. However, the fade detection delay (the time for fade data to be received by the MCS) would be reduced by approximately 0.12 s.

Based on the above, it is recommended that the 20-GHz beacon be used for fade detection at 20 GHz. Figure 3-24 shows the hardware configuration. Periodic beacon power level measurements are made and the data transmitted to the MCS via the orderwire.

Similar options are available at 30 GHz. The communications signal power may be measured directly on board; however, the same limited operating range noted previously at 20 GHz would be encountered. Alternatively, a 30-GHz beacon could be installed on board and power could be measured at the ground station. This method is somewhat complicated (as noted in Subsection 3.7), but feasible. Finally, a pilot signal could be added to the 30-GHz up-link. This pilot would necessarily be operated in a burst mode which would create severe acquisition and measurement problems. Accurate measurement over a substantial range of fades requires high nominal C/N. To meet this requirement with minimal power requires a very narrowband signal and the use of a narrowband phase-locked loop (PLL) receiver. Such a receiver has an inherent acquisition and lock-up time which is much too long for burst signal measurement. Widening the loop bandwidth sufficiently to provide the necessary speed of acquisition would seriously degrade the C/N.

Of the above schemes, only the beacon scheme is capable of providing accurate measurement over a wide fade range without undue equipment cost. Thus, it is recommended that this scheme be adopted for 30-GHz fade measurement. Figure 3-29 shows the hardware configuration for this scheme and Table 4-5 provides a link budget. This method would provide accurate measurement over a fade range of 20 to 25 dB. As with the 20-GHz beacon, the measurement data are collected by the terminal controller and sent to the MCS via the orderwire. The complete CPS fade detection system is shown in Figure 4-22.

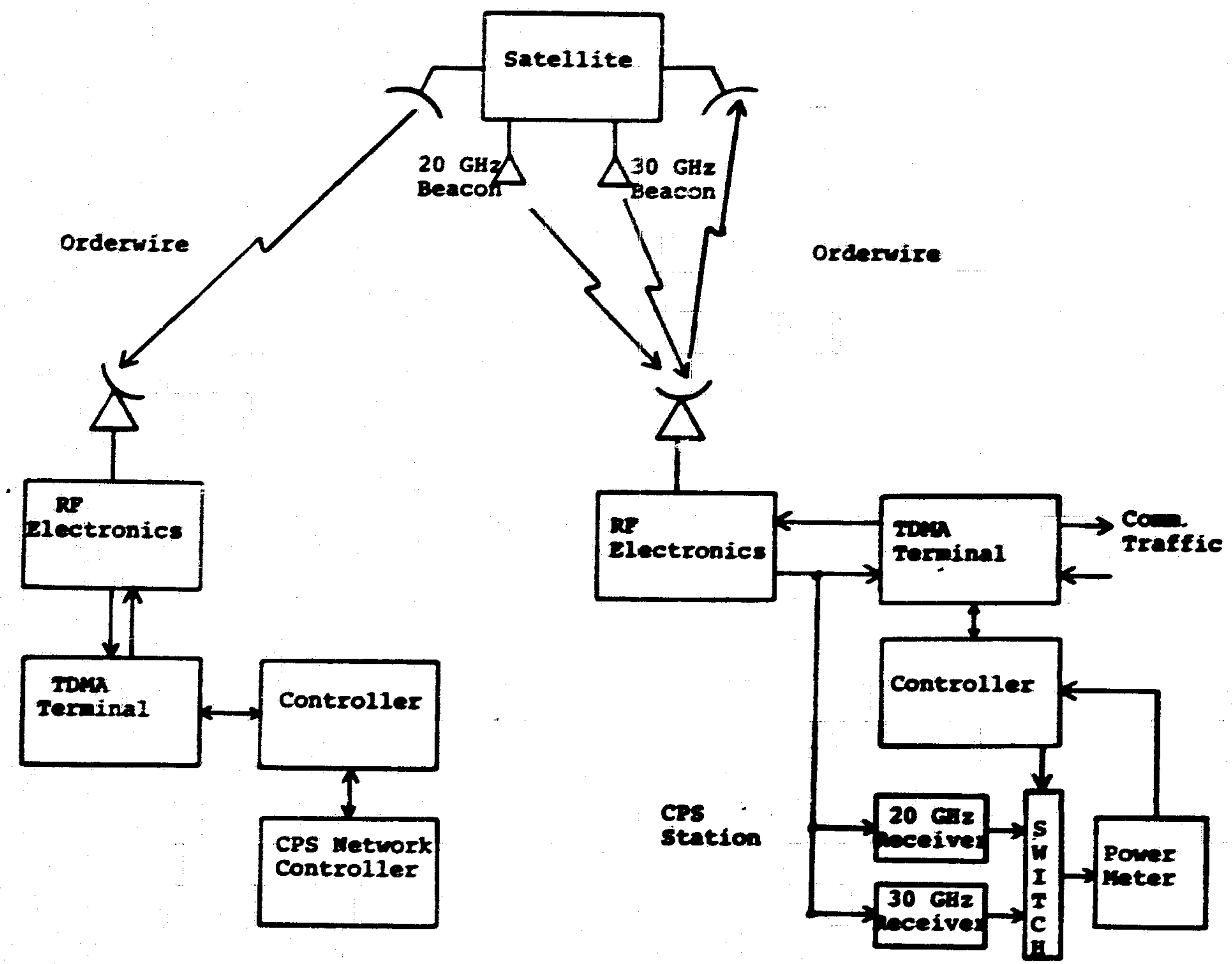

Figure 4-22. CPS Fade Detection

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Table 4-5. 30-GHz Beacon Link Budget (CPS)

Beacon Power	0 dBW
Transmit Antenna Gain	30 dB
e.i.r.p.	30 dBW
Path Loss	-213 dB
Receive Antenna Gain (3 m)	57 dB
Receive Signal Power	-126 dBW
Coupling Loss	-20 dB
System Temperature, T	28 dB
C/kT (K = 228.6 dB/°K)	55 dB
PLL Bandwidth	23 dB-Hz
C/N	32 dB

4.8 ADAPTIVE FEC CONTROL

In the event of significant path fades resulting from rain, CPS stations will increase link margins through the use of FEC and/or data rate reduction. These two techniques may be applied in different ways, both separately and together. This subsection discusses these techniques and various implementation options.

4.8.1 DATA RATE REDUCTION

One method of increasing link E_b/N_o is to simply reduce the burst data rate. The data rate can be traded dB for dB with E_b/N_o; that is, a 50-percent (3-dB) reduction in data rate results in an increase in E_b/N_o of 3 dB. A reduction in data rate requires changes in the modem filters and clocking rate. In addition, either the throughput must be reduced or the TDMA burst duration increased, with significant impacts on the terrestrial interface. Since changes in throughput or burst duration are also required for FEC, they are discussed in a separate subsection (4.8.3) and the discussion here is limited to modem impacts.

The modem hardware modifications required for data rate reduction depend upon the modulation technique used. At present two modulation methods are under consideration, QPSK and MSK. A QPSK modulator structure is shown in Figure 4-23. Data rate reduction can be accommodated in two ways. One way is by reducing the clocking rate in the serial-to-parallel (2-bit parallel) converter and narrowing the symbol filters to accommodate the narrower baseband spectrum. This method reduces the RF signal bandwidth by the amount of the rate reduction and requires an additional pair of symbol filters. On the receive side, the symbol and clock recovery filters must be changed and the clock rate reduced. This method is shown in Figure 4-24.

A second rate reduction implementation available with QPSK is a conversion from QPSK to BPSK. This is easily accomplished by reducing the data clock rate and applying each bit simultaneously to both quadrature channels. This effectively modifies the signal structure as shown in Figure 4-25. A similar change is required in the demodulator. Since each symbol now conveys only one bit, rather than two, the information rate reduction leaves the symbol rate, and thus the signal bandwidth, unchanged and new symbol filters are not needed. This method is significantly simpler and is recommended. A simplified diagram of this method is shown in Figure 4-26.

Rate reduction with SMSK requires the same kind of filter and VCO modifications as the first QPSK method discussed

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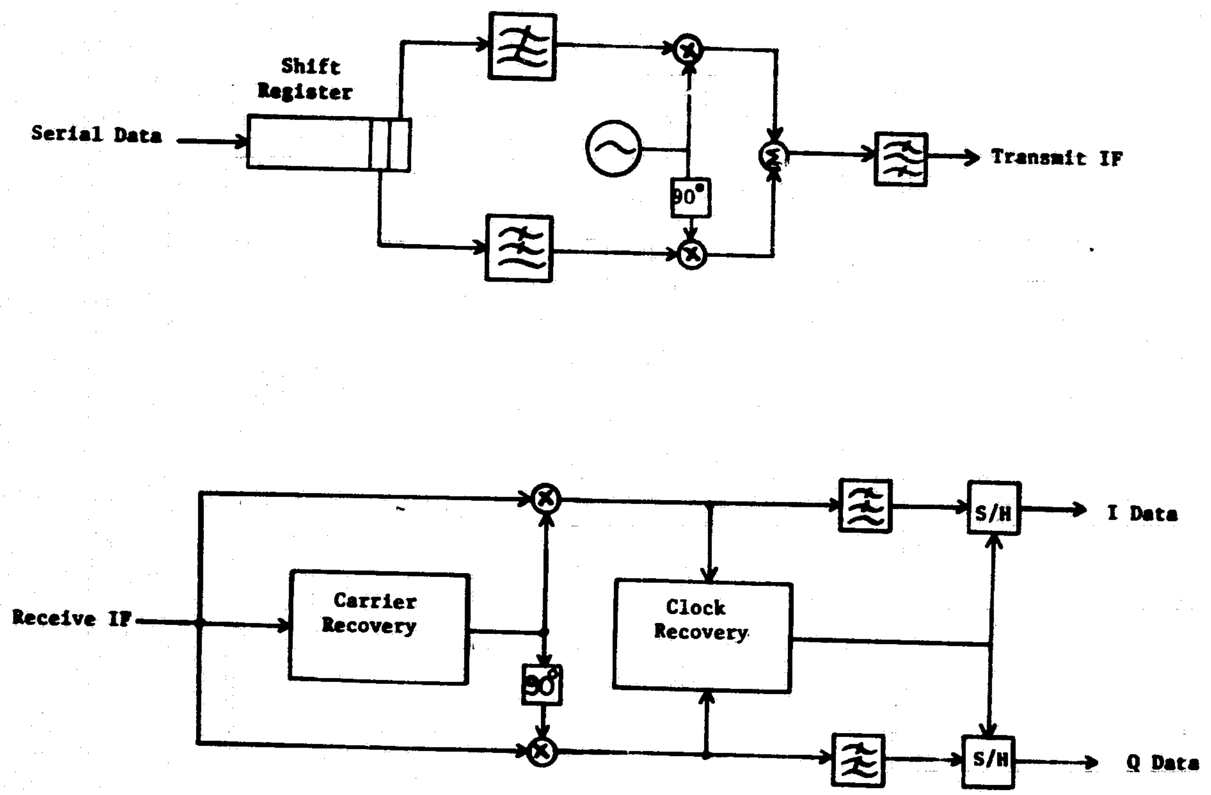

Figure 4-23. QPSK Modulator/Demodulator

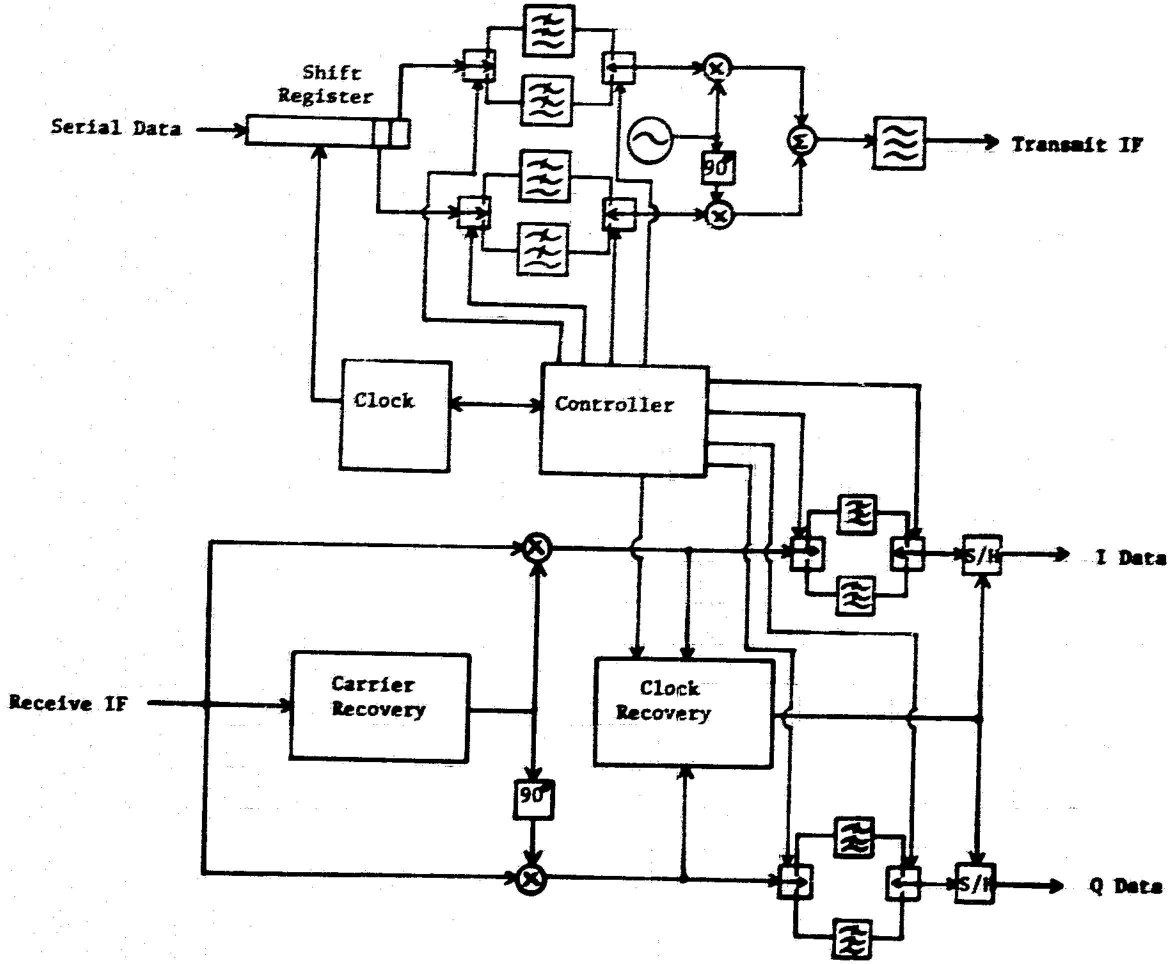

Figure 4-24. QPSK Symbol Rate Reduction

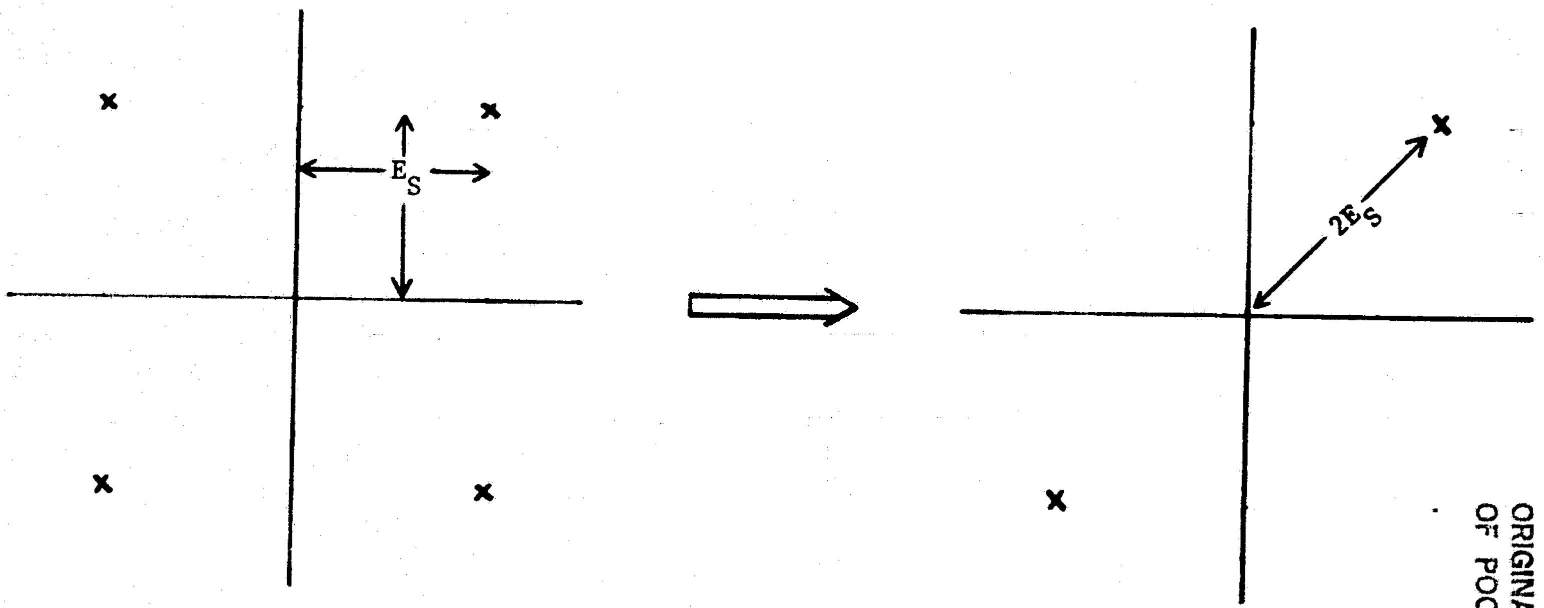

Figure 4-25. Signal Structure--QPSK to BPSK

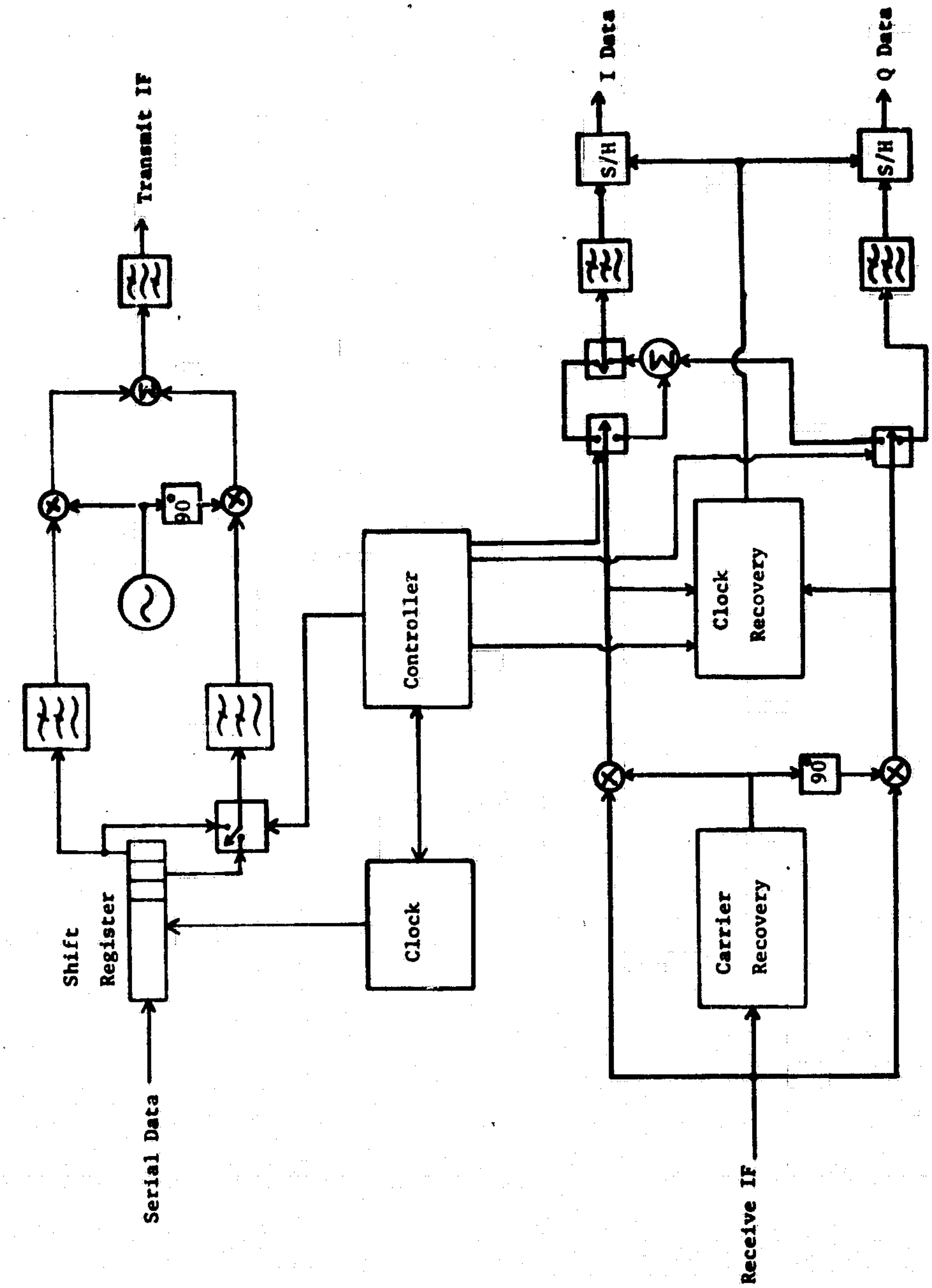

Figure 4-26. QPSK Modem With Selectable BPSK Mode

previously. The prototype SMSK modulator and demodulator are shown in Figure 4-27. While the modulator can be practically realized, construction of a demodulator matched filter of significant precision is difficult at microwave frequencies and the low-pass equivalent baseband implementation shown in Figure 4-28 has been selected. The quadrature baseband lattice filter network (h_1, h_2) has been implemented in several ways, including as a single quadrature hybrid (which included the summers). In any event, rate reduction would require changing the modulator filter, the transmit clock rate, the receiver symbol filter network, and the clock VCO quiescent frequency. A diagram of such a configuration is shown in Figure 4-29. These changes are comparable in complexity to those required for the first QPSK method described previously.

Rate reduction by a method similar to the second QPSK method is not possible due to the non-quadrature nature of the SMSK modulator. A reduction in data rate without filter modification would produce an erroneous, non-MSK signal.

4.8.2 FORWARD ERROR CORRECTION

Forward error correction (FEC) introduces systematic redundancy into the data stream to permit error correction at the receiver. This achieves a lower bit error rate (BER) for a given E_b/N_o, or equivalently, a lower required E_b/N_o for a desired BER. In a system with fixed, non-adaptive FEC, the additional symbols are accommodated by increasing the symbol rate and thus the bandwidth. Since it would be undesirable to allocate excess bandwidth for each channel to be used only during rain events, it is assumed that the additional symbols must be accommodated by

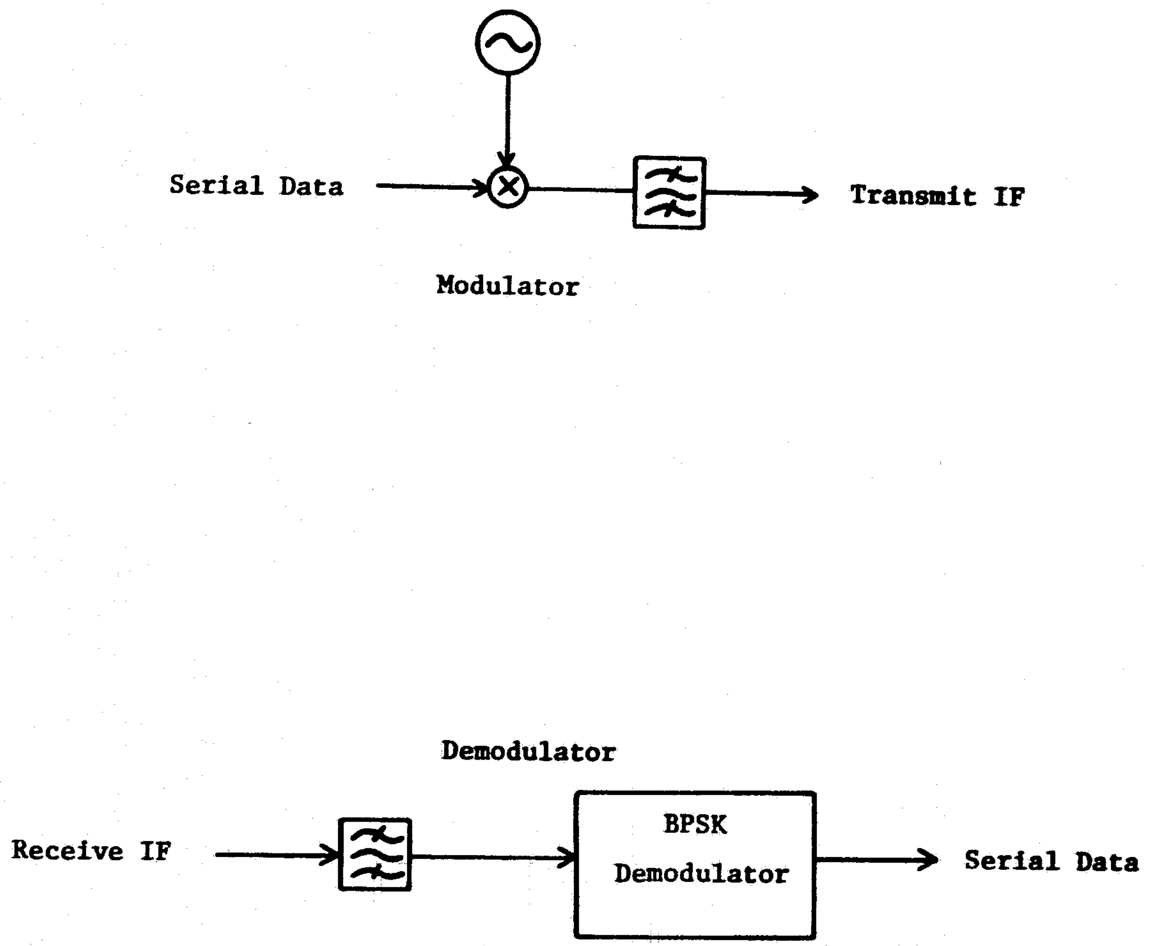

Figure 4-27. SMSK Modulator/Demodulator Theory

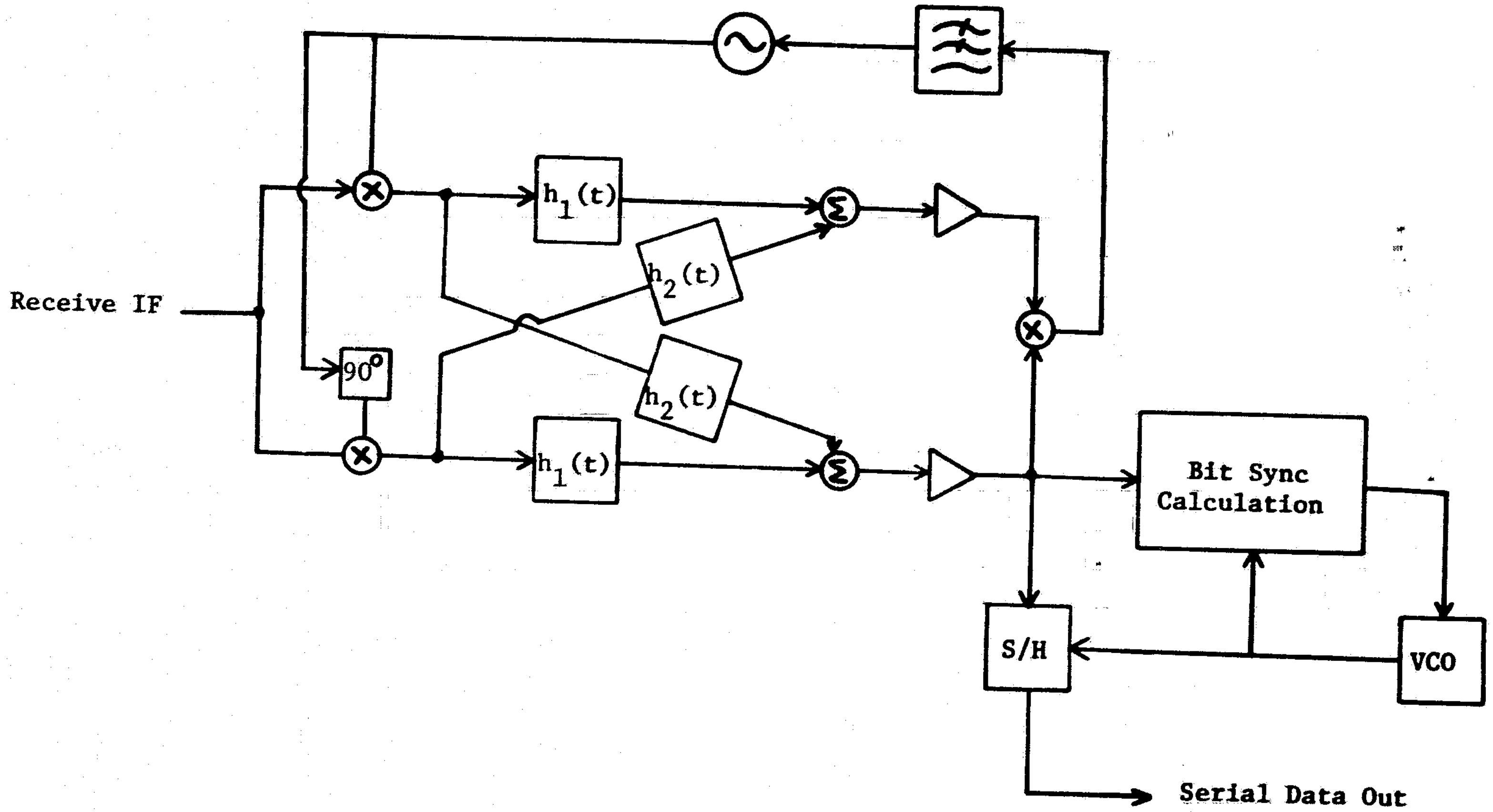

Figure 4-28. Practical SMSK Demodulator

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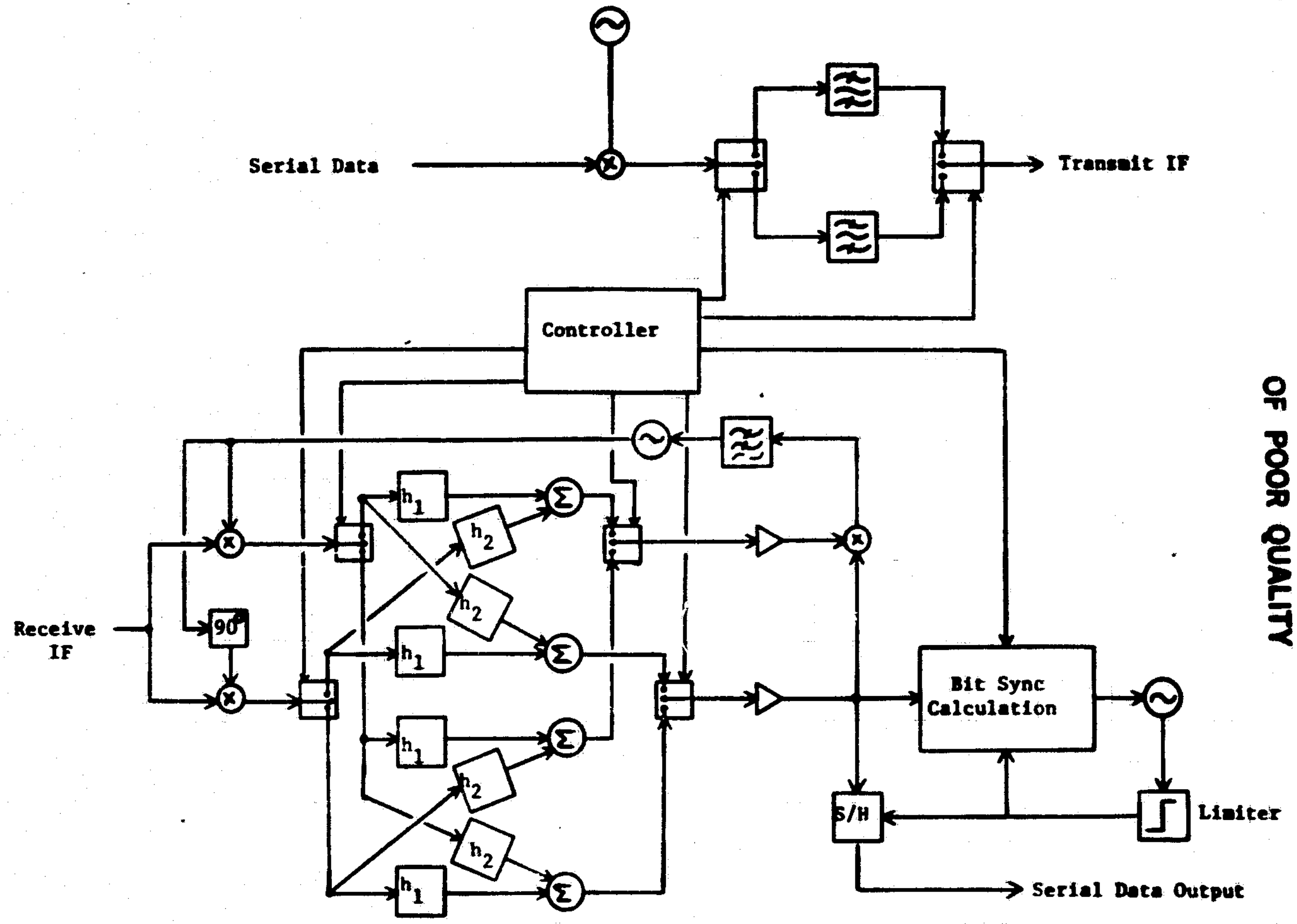

Figure 4-29. SMSK Symbol Rate Reduction

either a reduction in throughput or by TDMA burst expansion. Since code performance is usually specified under the assumption that the symbol rate is increased to accommodate the code symbols, accommodation via throughput reduction or burst expansion provides an additional gain in E_b/N_o equal to the inverse of the code rate (i.e., rate 1/2 provides coding gain +3 dB).

Both burst expansion and throughput reduction require adjustments by the terrestrial interface. In addition, burst expansion requires restructuring of the TDMA frame. These issues are discussed in Subsection 4.8.3. The modem modifications are shown in Figure 4-30 and consist of switching hardware controlled by the terminal controller.

FEC code selection is a compromise between the conflicting requirements of high coding gain (defined as the reduction in required E_b/N_o for a given BER) and ease of implementation, both for high-speed operation and space use.

The characteristics of various FEC coding techniques are shown in Table 4-6. Practical codes can be divided basically into two classes: block and convolutional. Short block codes, such as the BCH and Golay codes, can be decoded using hard decision, table look-up methods and thus can be operated at high speeds; however, they provide relatively low gain. Soft-decision block decoding is much more complex and limited in operating speed, but provides considerably more gain. The highest gains are obtained with convolutional coding techniques. Of these, sequential decoding provides the greatest coding gain but is limited to low speeds. Viterbi decoding provides nearly as high gain and is capable of high-speed operation. Concatenated techniques, utilizing a short inner code which can be soft-decision decoded and a Reed-Solomon nonbinary BCH outer code, have

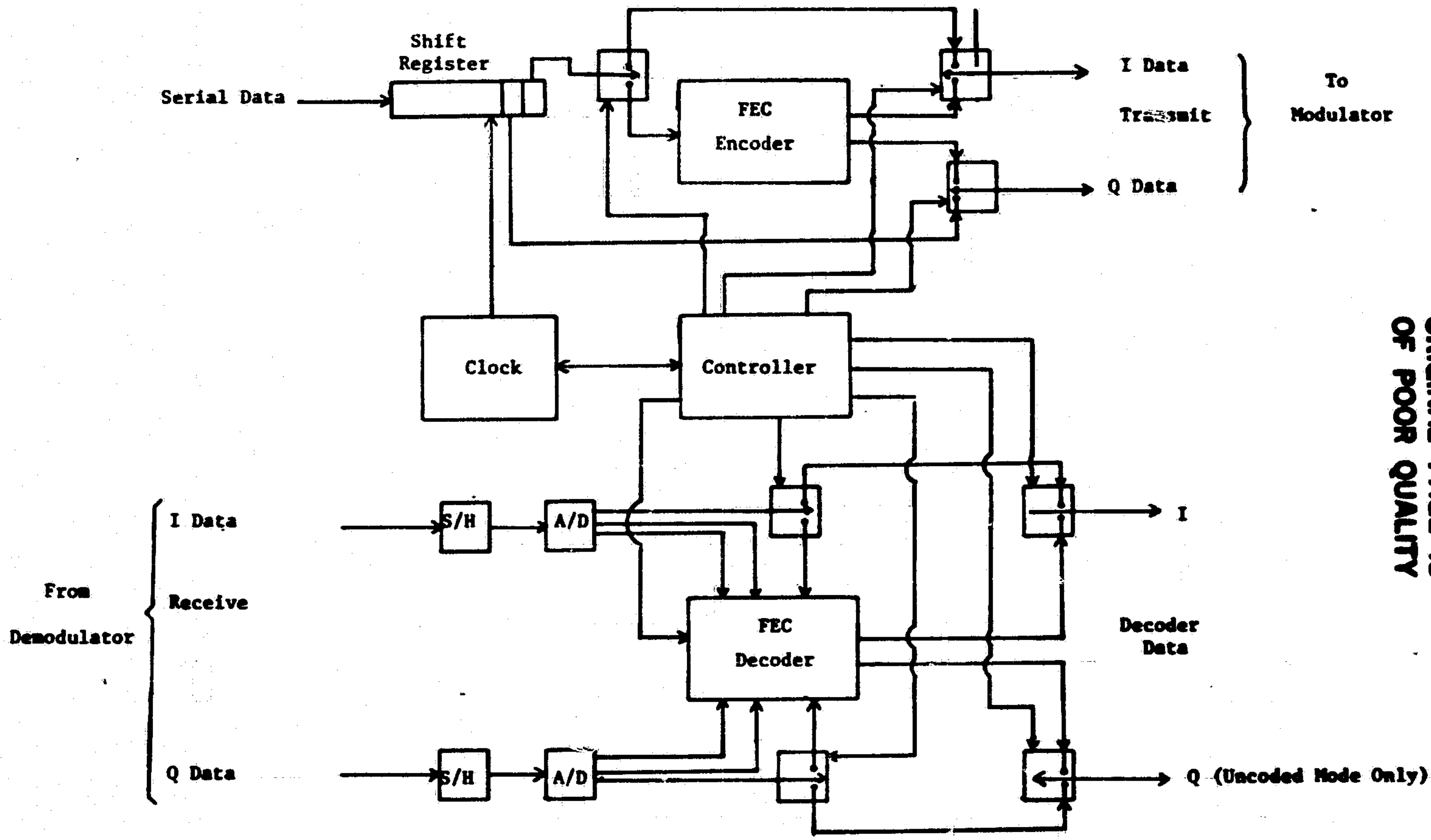

Figure 4-30. FEC Switching

Table 4-6. FEC Code Characteristics

Code	Decision	Gain[a]	Complexity	Speed[b]	Bandwidth[c]
Rate 1/3 Convolutional/ Viterbi	Soft	5.4	Med	Med	3
Rate 1/2 Convolutional/ Sequential	Soft	3.8-5.6[d]	High	Low	2
Rate 1/2 Convolutional/ Viterbi	Soft	5.1	Med	Med	2
Rate 1/2 Concatenated	Soft	5.0	High	Med	2
Rate 3/4 Convolutional/ Viterbi	Soft	4.2	Med	Med	1.33
Rate 1/2 Golay	Soft	4.0	High	Med	2
Coded Octal Phase	Soft	3.4	Med	Med	1
Rate 7/8 BCH	Hard	2.4	Low	High	1.13
Rate 1/2 Golay	Hard	2.1	Low	High	2

[a] BER = 10^{-5}.
[b] Low ≈10 Mbit/s, Med = 50-120 Mbit/s, High > 120 Mbit/s with current technology.
[c] Bandwidth expansion factor.
[d] Performance depends on implementation and operating speed.

provided nearly as high gain and appear to possess a significant speed advantage. Coded phase modulation is an integrated coding/modulation technique. The version considered here uses 8-phase PSK combined with rate 2/3 convolutional encoding and Viterbi decoding. While coding and modulation are often regarded as distinct, they are closely related. Integrated modulation-coding techniques are potentially capable of superior performance, particularly in band-limited channels. The coded phase technique provides significant coding gain and, in this version, requires no bandwidth expansion, unlike most other techniques which increase transmission bandwidth by the inverse of the code rate.

The foregoing comments regarding speed and complexity are necessarily relative due to their dependence on integrated circuit technology (speed, density, and power consumption) which is evolving rapidly. Sub-micrometer lithography and GaAs FET technology promise to have major impacts in the future.

In a given code class, diminishing returns are obtained for more and more intensive coding. For example, a rate 1/2 convolutional code with Viterbi decoding provides roughly 5-dB coding gain, while a rate 1/3 code requiring 50-percent greater reduction in throughput (or increase in burst size) provides less than 1-dB additional gain. Because of this, rate 1/2 encoding has been selected as a good compromise level of coding.

A major concern is the feasiblity of a space-qualified LSI decoder implementation. Space, mass, and power constraints dictate a largely, if not entirely, LSI implementation. In all practical cases, encoding hardware is trivial; it is the decoding hardware that dictates the code choice. Two groups have built and tested LSI Viterbi decoders at rates up to 40 Mbit/s [29],[30]. Based on tests performed using a TTL MSI implementation, a concatenated code with similar performance appears to be feasible in LSI; however, this has not been demonstrated.

4.8.3 THROUGHPUT REDUCTION AND BURST EXPANSION

Both rate reduction and FEC require that the information transmission rate be reduced.

A reduction in information rate can be accommodated by either a reduction in actual information throughput or an increase in TDMA burst duration.

Throughput reduction in a TDMA terminal can be effected as shown in Figure 4-31, which shows the terrestrial interface buffer (TIB). In a typical TIB, data on each terrestrial channel are serial-to-parallel converted in the shift register and clocked into one of two memories. Data to be sent in sucessive bursts are stored in different memories. Thus, the current burst data can be clocked out of one memory while the next burst data are clocked into the other. During burst transmission, data for each terrestrial channel are clocked in turn out of the appropriate memory, parallel to serial converted and input to the burst formatter. This unit combines the data and preamble to form the burst data stream which is fed to the modulator. Throughput reduction is accomplished by reducing the clock rate to the TIB and removing one or more of the TIMs from the memory address sequence. This reduces the volume of transmitted data to maintain the same burst size. Similar modifications to clock rate and TIM addressing occur on the receive side.

Throughput reduction would maintain link quality at a cost of reduced capacity. This would complicate the terrestrial

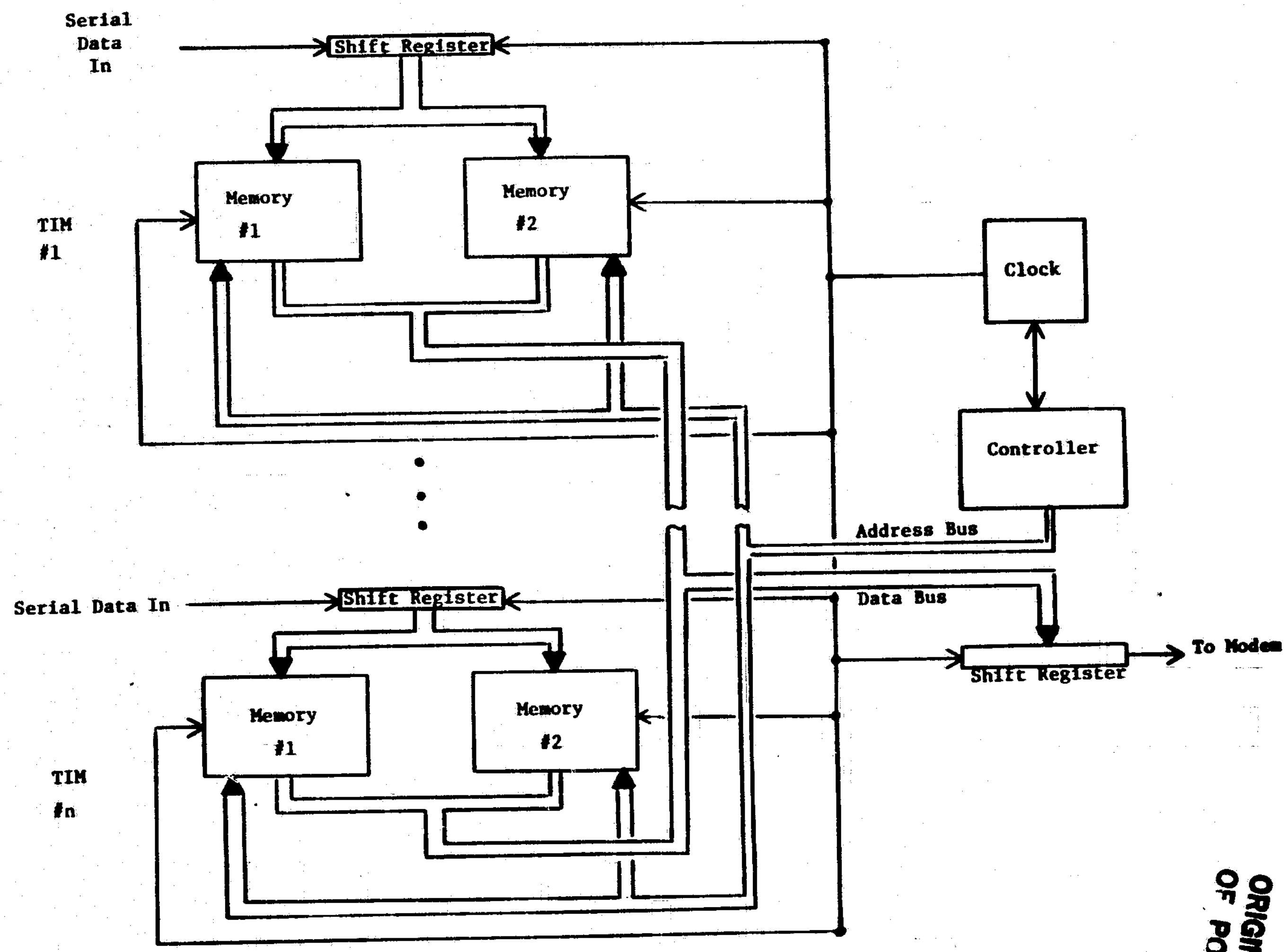

Figure 4-31. Terrestrial Interface

interface and the establishment of tarriffs, particularly if the terrestrial segment and satellite-earth-station segment owners were different entries. These problems could be resolved. For example, a user could pay a discount rate for channels which may experience outages during heavy rain. In another situation, a telephone company supplying a number of long-distance dial-up trunks could render a number of them "busy" for the duration of the rain event.

In burst expansion, a portion of TDMA frame time is held in reserve and allocated dynamically to terminals experiencing rain fades. Such a scheme has been studied by Acampora [31], [32], and shows considerable promise. The additional frame time may be used in two ways: the degraded user may transmit an additional burst, or it may expand its original burst and reassign the remaining bursts. While the former scheme requires a simpler frame reassignment, the latter requires no overhead, (burst sync preamble). Since frame assignment requires only 1 s, the latter scheme is preferred.

Burst expansion requires a reduction in TIM clocking and change in burst timing (scheduling) which requires interaction with the MCS. Burst timing changes involve demand assignment processing as described in Subsection 4.6. Based on information received via the orderwire, the terminal controller reschedules the burst effective with the first frame of the next assignment frame. The TIM clocking rate is simultaneously reduced. Burst expansion has the major advantage of negligible impact upon the terrestrial channels. If unused frame time is available, it is to be preferred over rate reduction.

Due to the on-board regeneration, the hardware adjustments outlined for the transmit and receive equipment must also occur on board the satellite. The MCS controls these adjustments via the TT&C link in a manner analagous to its control of the terminals via the orderwire.

4.8.4 NETWORK ADAPTATION AND CONTROL

The various adaptation options are summarized in Table 4-7. From a standpoint of maximum gain with minimum degradation, it is clear that the best adaptation strategy is to first introduce FEC and then resort to rate reduction if further gain is required. In either case, burst expansion should be used if unused frame time is available; if not, throughput should be reduced.

Table 4-7. Adaptation Options

Option	Throughput	Burst Duration	E_b/N_o Gain (dB)
FEC, Burst Expansion	Unchanged	Doubled	7
Rate Reduction, Burst Expansion	Unchanged	Doubled	3
FEC, Rate Reduction, Burst Expansion	Unchanged	Quadrupled	10
FEC, Throughput Reduction	50 %	Unchanged	7
Rate Reduction, Throughput Reduction	50 %	Unchanged	3
FEC, Rate Reduction, Throughput Reduction	25 %	Unchanged	10

The fade control procedure is flowcharted in Figure 4-32. The MCS continuously monitors the fade data coming in over the orderwire. When a significant fade occurs, the MCS first attempts to allocate additional frame time for FEC or

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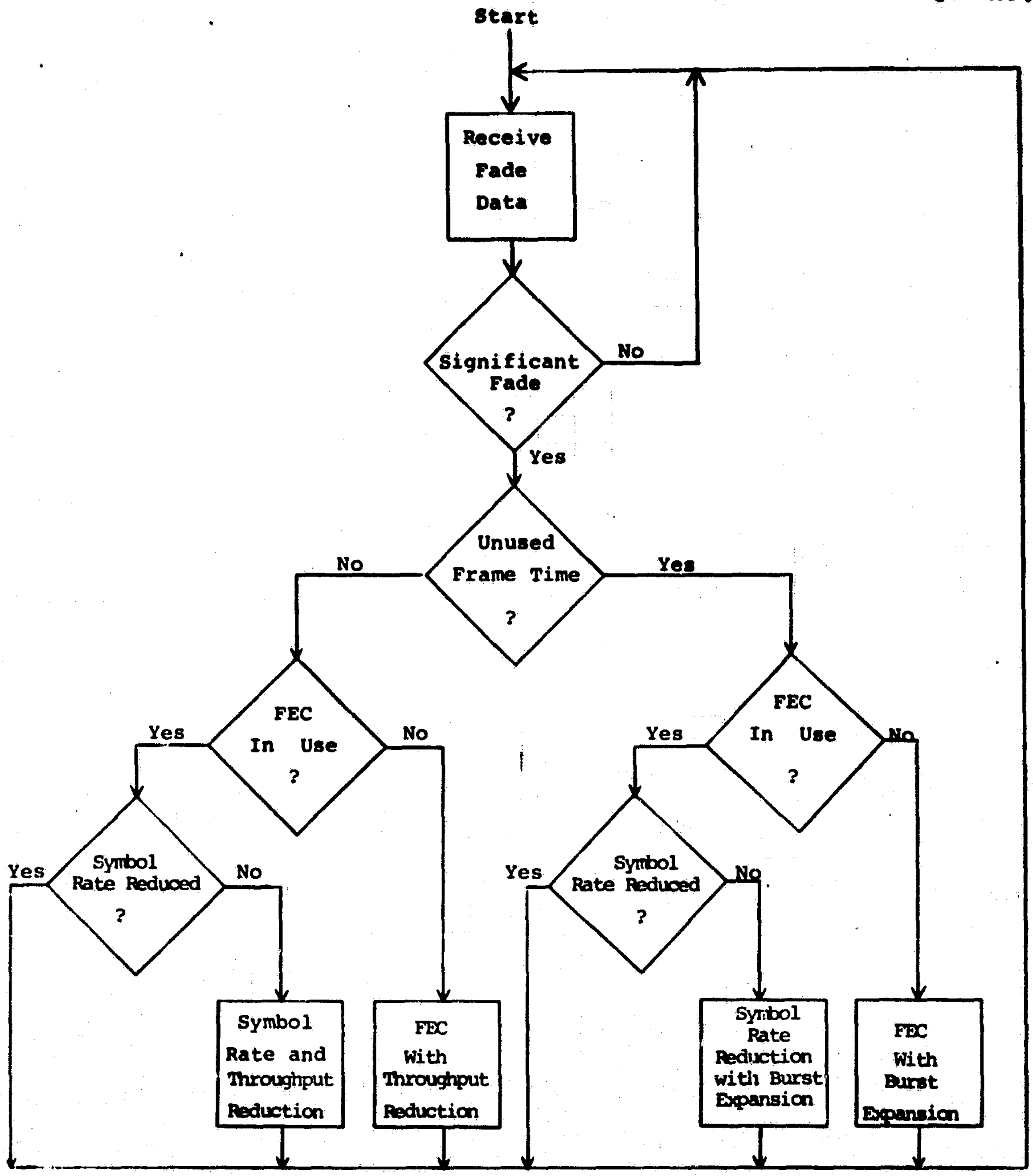

Figure 4-32. Fade Control Procedure

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symbol rate reduction. If none is available, throughput reduction is employed. The associated CPS station(s) is (are) notified via the orderwire and the on-board baseband processor, and modem control is notified by the TT&C link. Adaptation commences at the start of the next assignment frame.

A step-by-step breakdown of the sequence of events from fade to successful adaptation is shown in Table 4-8 with the worst-case time delays. The worst-case response time is 3.5 s, which corresponds to a maximum up-link fade of 3.5 dB and a down-link fade of 1.7 dB. These figures represent the minimum amount of built in margin required on the up-link and down-link.

Table 4-8. Adaptation Sequence and Delay

Burst Expansion	
Fade occurs at CPS station	0.00 s
CPS station waits for orderwire	1.00 s
Data sent to MCS	0.25 s
MCS determines adaptation and waits for start of assignment frame	1.00 s
New assignment frame sent to all users (includes propagation delay)	1.25 s
Total response time	3.50 s
Throughput Reduction	
CPS station waits for orderwire	1.00 s
Data sent to MCS	0.25 s
MCS orderwire response time	0.50 s
Instructions sent to CPS stations	0.25 s
Total	2.00 s

4.9 ON-BOARD OSCILLATOR CONTROL

The on-board clock control method based on drift measurements on the ground is still attractive for the on-board baseband processing system. Although the MCS reference timing can be recovered on the satellite by phase locking the on-board oscillator to the control burst UW pulses, reliable timing generation requires a rain fade margin of at least 40 dB at 30 GHz. In addition, a number of other issues associated with the on-board phase-locked loop approach must be resolved, including reliable ground reference clock system design and up-link interference.

The basic clock correction procedure for the CPS network shown in Figure 4-33 is similar to that for the trunk network except for phase error measurements. The MCS detects the receive frame timing from the down-link bursts and generates periodic pulses, which in turn increment the receive counter. The receive counter content is compared with the reference counter once every T seconds to generate a phase error. These counters are then reset at the beginning of the next measurement period. If the receive reference timing is lost because of a heavy rain fade, the receive counter will be extrapolated based on the past measurements. The same clock correction algorithm used for the trunk network can be employed to compute the correction data.

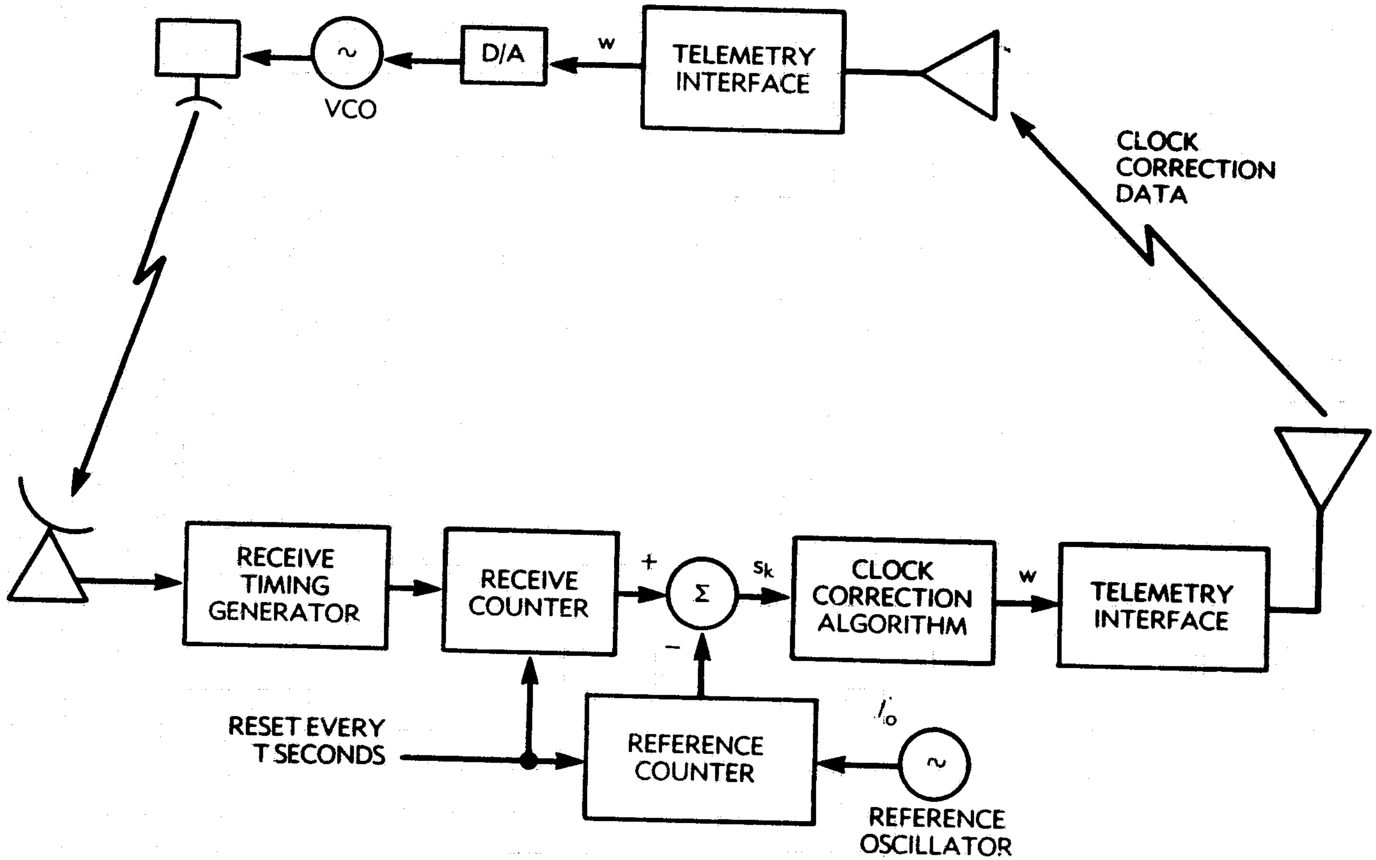

Figure 4-33. On-Board Oscillator Control for CPS Network

5. GROUND TERMINAL DESIGN

The major ground system components for the experimental system are shown in Figure 5-1. The ground segment consists of trunking stations with diversity terminals, large CPS stations with an antenna diameter of 5 meters, small CPS stations with an antenna diameter of 3 meters, and the master control station (MCS) located in Cleveland, Ohio. The two networks, trunk and CPS, operate independently, and only one network can be experimented with at one time. Overall network control as well as spacecraft processor control is performed from the MCS via orderwire channels and a TT&C link. This section presents ground terminal configurations, hardware and software processing functions, requirements, and design approaches for the experimental network stations.

5.1 TRUNKING STATION

The trunk system carries heavy point-to-point and point-to-multipoint traffic for large users which interconnect their hub offices scattered over major U.S. cities. The main features of the trunk system are:

a. SS-TDMA,
b. 256-Mbit/s burst rate,
c. 5-meter antenna,
d. spatial diversity,
e. rain fade margin of 18 dB for up-link and 8 dB for down-link without diversity, and
f. adaptive power control of 0 to 10 dB.

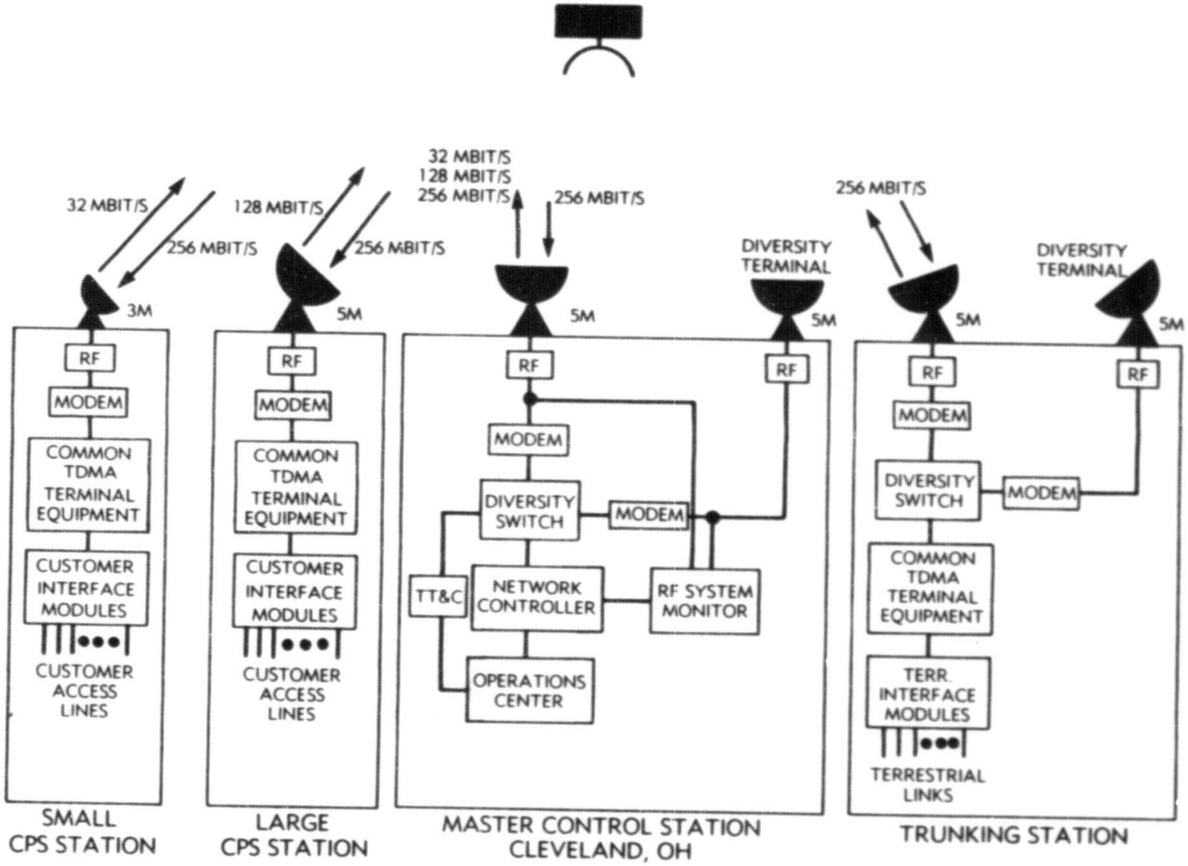

Figure 5-1. Experimental System Ground Terminals

A ground terminal configuration of the trunk system is shown in Figure 5-2. High availability and reliability are essential in designing a trunking station because it will carry a large number of traffic channels. These objectives are achieved by means of adaptive power control, spatial diversity, equipment module redundancy, and fault-tolerant hardware and software design. The system can accommodate various types of terrestrial trunk traffic. Terrestrial network interface can be a mix of analog multiplex hierarchy (groups, supergroups, and mastergroups) and digital PCM hierarchy (T1, T2, and T3), with the latter being the major future terrestrial network transmission. Analog multiplexed signals are converted to the standard digital formats prior to TDMA burst formation. In the selection of a diversity site, the geographic correlation of atmospheric precipitation at the main and diversity locations must be considered. The transmission link between the two sites can be a line-of-sight microwave link or fiber optic link, depending on their geographical suitability.

5.1.1 RF EQUIPMENT CONFIGURATION

An RF equipment configuration is shown in Figure 5-3. The trunking station employs an antenna diameter of 5 meters with a 61.5-dB transmit gain (60-percent efficiency) at 28.8 GHz and 57.6-dB receive gain at 19 GHz. The normal transmit TWTA power is 650 W at saturation and 52 W (11-dB backoff) in the clear sky condition. Rain fade is adaptively controlled up to 10 dB by increasing the transmit power to near saturation (1 dB below

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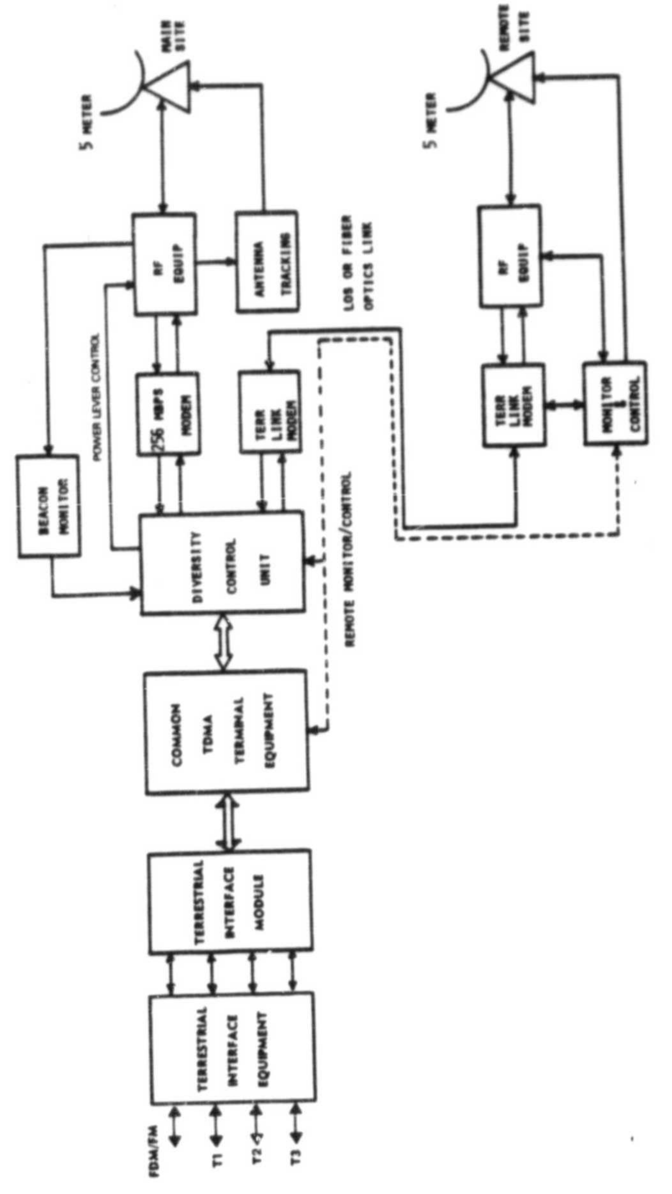

Figure 5-2. Trunking Station

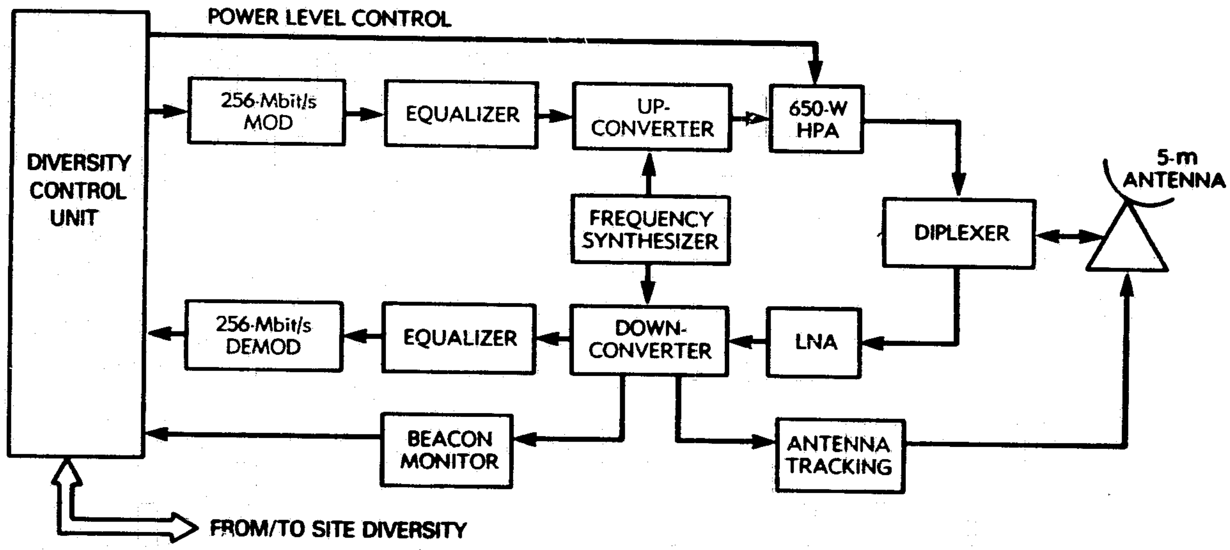

Figure 5-3. RF Equipment Configuration

saturation). The earth station G/T is 29.8 dB/K, and the combined E_b/N_o is 15.3 dB with an 18-dB up-link fade and 8-dB down-link fade.

5.1.2 SPACE DIVERSITY CONTROL UNIT

A space diversity control unit, shown in Figure 5-4, measures the link fades at the main and diversity sites and selects one with better performance. Diversity switching is simultaneously executed on the up-link and down-link pair during the guard time without loss of data.

The differential electrical path delay between the main and diversity sites is compensated by a fixed delay in the main path and a variable delay in the diversity path. The fixed delay is approximately equal to the propagation time from the main terminal to the diversity terminal, and any other delays (dynamic or fixed) are adjusted by the variable delay elements. The receive signal is first demodulated and reclocked using an elastic buffer, and the variable delay value is dynamically adjusted such that the reference unique words from the two sites arrive at the receive switch at the same time. The transmit path delay is adjusted by a special burst transmitted from a secondary site.

Link fades can be measured by the unique word (UW) bit error rate (BER), pseudo BER, or beacon method. The first technique is simple but relatively time consuming to measure a low-channel BER (10^{-6} or lower). The second technique accelerates the BER measurement by setting up artificial bit decision thresholds in the demodulator. A more accurate fade measurement is performed by monitoring beacon power level over a wide dynamic range. Diversity switch control does not require an MCS command

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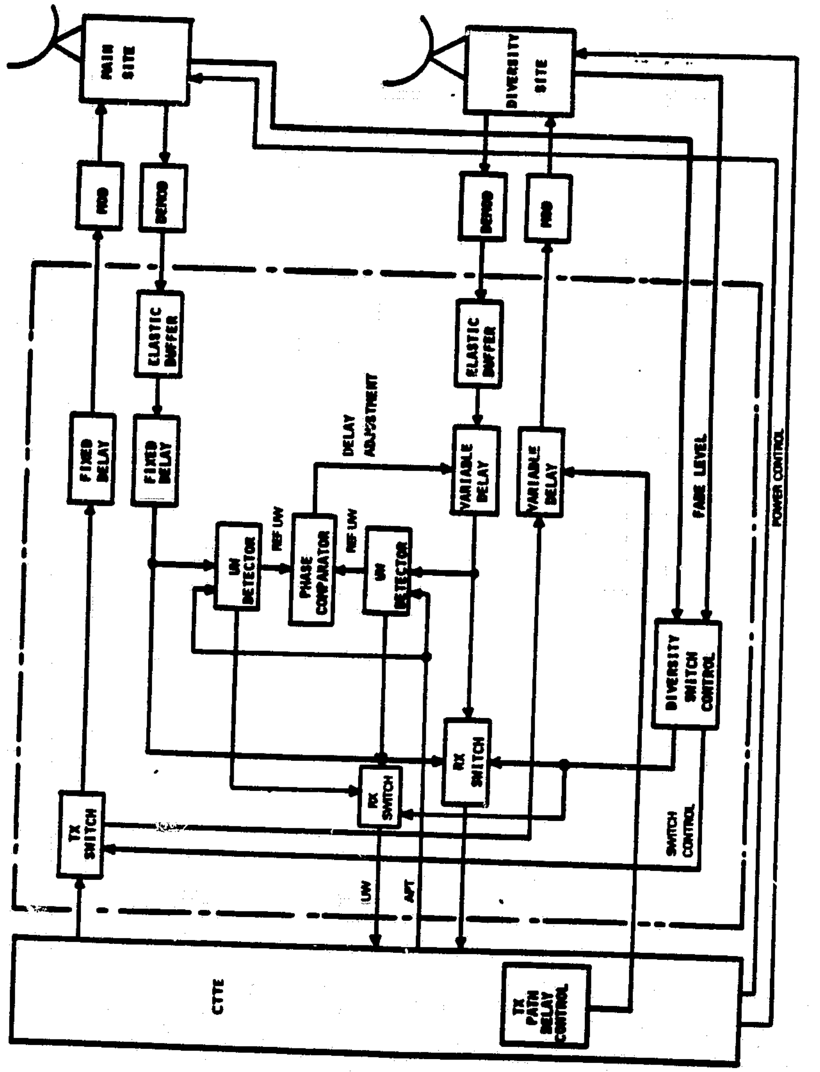

Figure 5-4. Space Diversity Control Unit

and is done locally because the bursts received from the main and diversity sites experience the same up-link fades.

The transmit path delay can be adjusted by calibrating the diversity path length with a special loopback signal at the main site. However, this procedure requires additional equipment and does not provide an accurate delay measurement. An alternate approach is to transmit a diversity burst from the secondary site as shown in Figure 5-5. The trunking station transmits orderwire and traffic bursts from the primary or active site (the main or diversity site). The diversity burst (also called a preamble burst or dummy burst), consisting of the carrier and bit timing recovery (CBTR) and UW patterns, is transmitted from the alternate site at the end of the TDMA frame and detected at the MCS. The timing error of the diversity burst is measured relative to the orderwire burst position, and error control data are sent to the trunking station via the reference burst orderwire. The diversity burst slot can be time-shared by other trunking stations in the same beam. A closed-loop delay measurement is also possible using a loopback switch state.

5.1.3 COMMON TDMA TERMINAL EQUIPMENT

The common TDMA terminal equipment (CTTE), along with terrestrial interface modules (TIMs), establishes a data transmission link between terrestrial and satellite networks by converting traffic data to a proper form for transmission. Space segment access is controlled by the MCS orderwire, while the terrestrial traffic processing is performed in accordance with the station channel assignment. Extensive software processing and

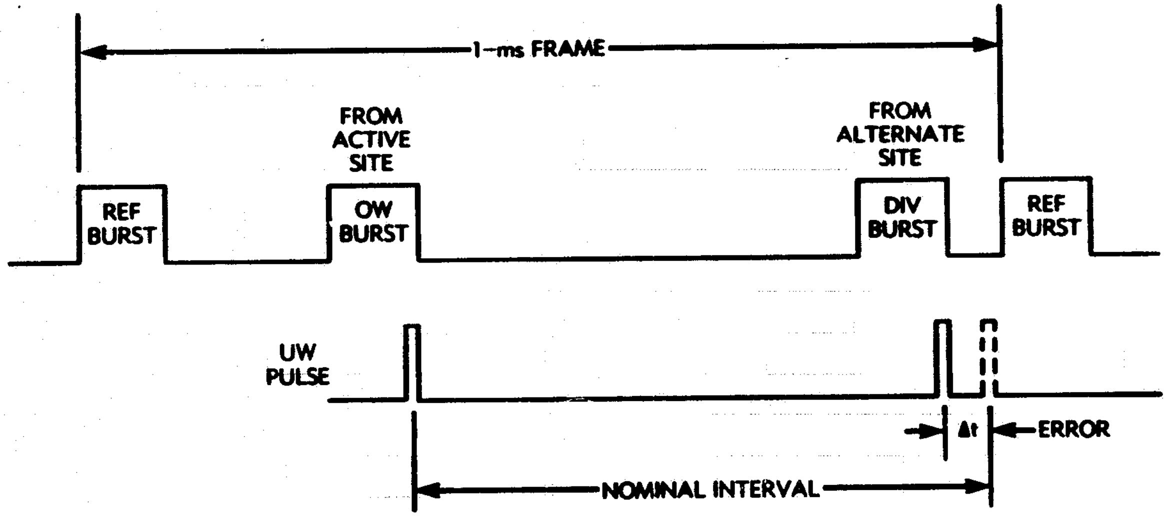

Figure 5-5. Transmit Path Delay Adjustment

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high-speed hardware functions are required to maintain reliable system operation.

Figure 5-6 is a general block diagram of the trunk CTTE. The UW detector correlates the incoming bit stream with a predetermined UW pattern and generates a detection pulse gated with an aperture signal when the two patterns match within several bits (error threshold). The reference burst UW pulse along with the receive burst time plan (BTP) determines the expected arrival times of orderwire and traffic bursts, and an aperture window for each subsequent burst is generated to detect the precise burst position. The data field of a burst is descrambled and routed to the orderwire and data demultiplexers for processing.

The transmit processing includes traffic and orderwire data multiplexing, scrambling, and preamble generation. The exact burst transmit times are determined by the transmit burst time plan and transmit frame timing, which is corrected once every control frame. Figure 5-7 is a functional block diagram of burst processing and timing control.

The orderwire demultiplexer separates various station control data from the MCS orderwire and routes them to proper processing units. Typical receive orderwire data are as follows:

a. initial acquisition timing data,
b. transmit synchronization data,
c. frame ID number for network synchronization,
d. transmit and receive BTPs,
e. power control data,
f. MCS status and other control data.

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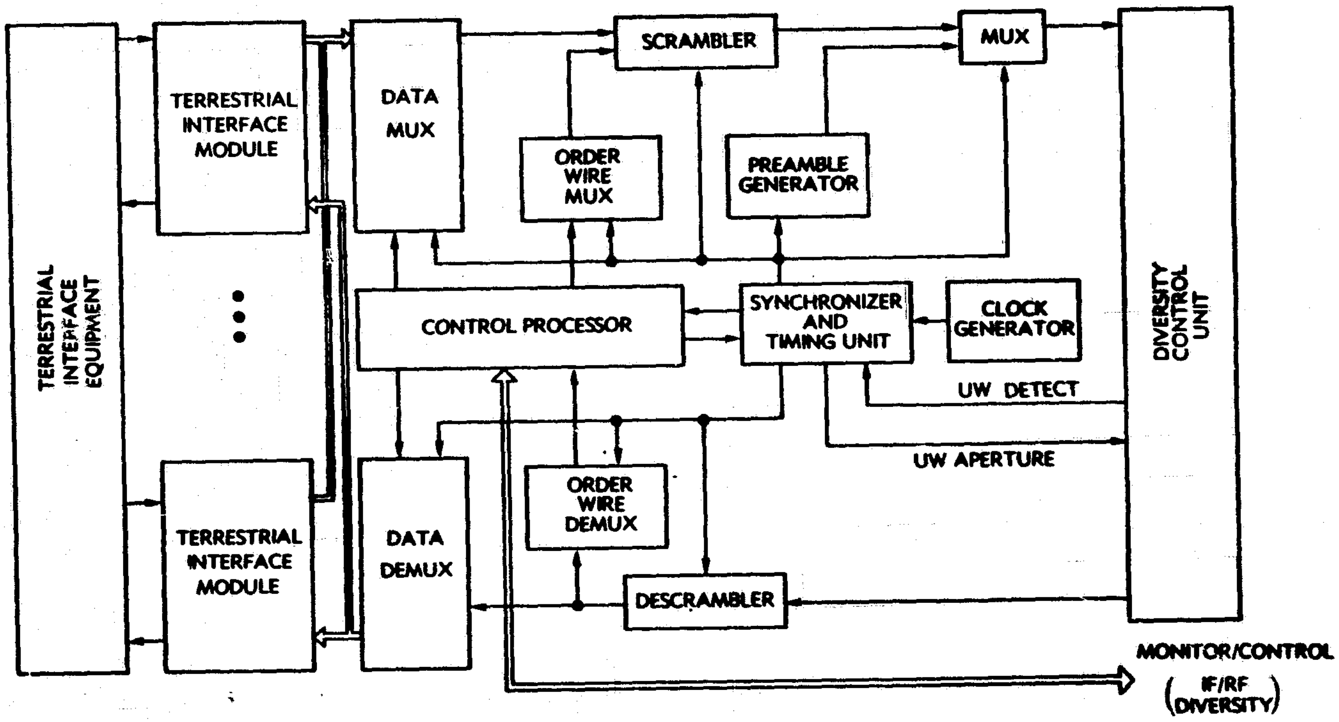

Figure 5-6. CTTE Block Diagram

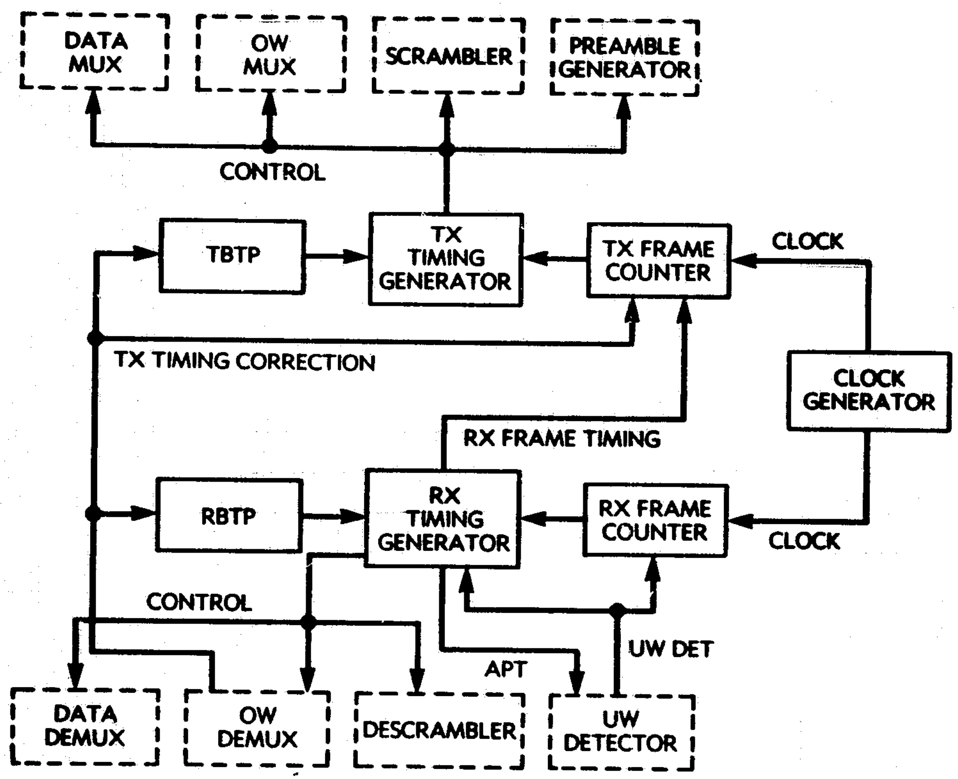

Figure 5-7. Burst Processing and Timing Control

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The transmit orderwire data inform the MCS of the trunking station status and request additional channel allocation. These data include the following:

a. channel requests,
b. rain fade data,
c. BER data,
d. diversity terminal status, and
e. station status.

The CTTE consists of six microprocessor modules which interactively perform necessary processing functions for trunking station operation. These processing modules and their functions are shown in Figure 5-8.

5.1.4 TERRESTRIAL INTERFACE MODULE

A typical TIM module is shown in Figure 5-9. Bursty high-speed data from the CTTE are routed to an expansion buffer via a data bus, which smooths the incoming data stream and generates a continuous terrestrial bit stream. Shown in the figure is an alternate (or ping-pong) buffer structure which allows one buffer to be written while the other is being read. The output of the expansion buffer is formatted according to the terrestrial transmission signal format, e.g., DS-1, DS-2, or DS-3. The subsequent buffer absorbs the timing error caused by plesiochronous network operation, Doppler shift, and on-board clock correction.

The TIM accepts a continuous serial data stream from terrestrial interface equipment and reformats it for satellite

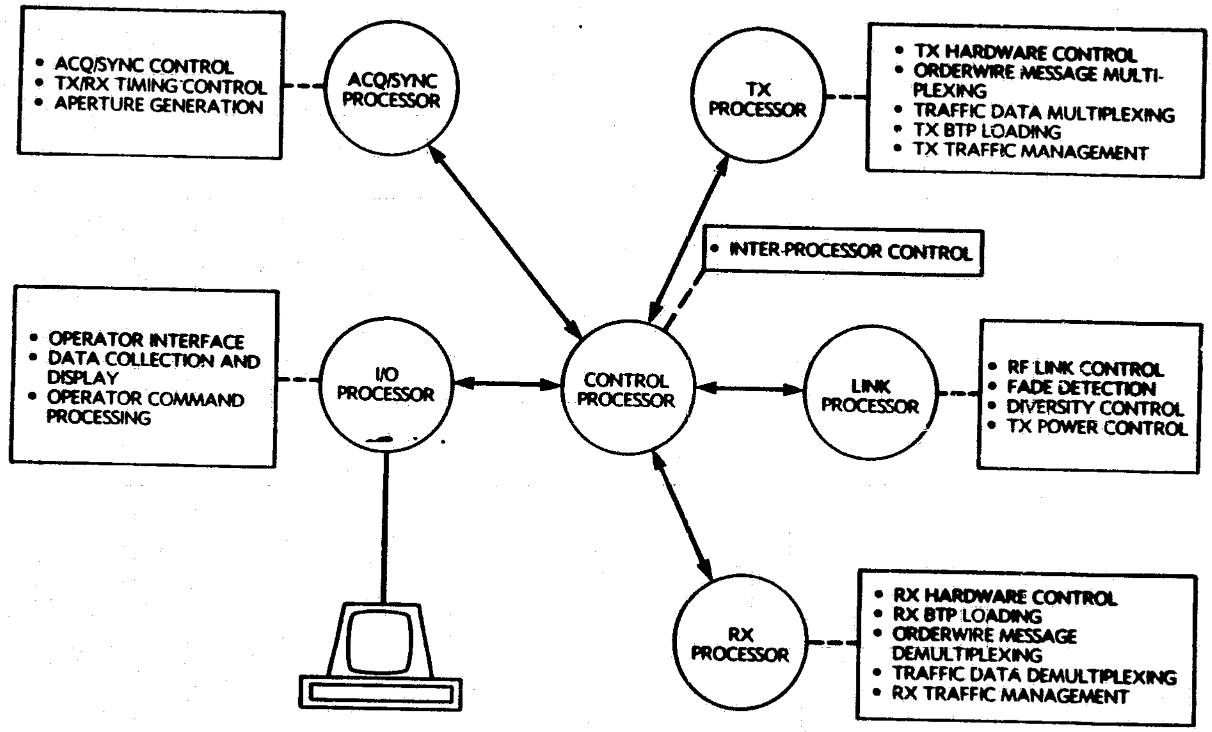

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Figure 5-8. CTTE Processor Configuration

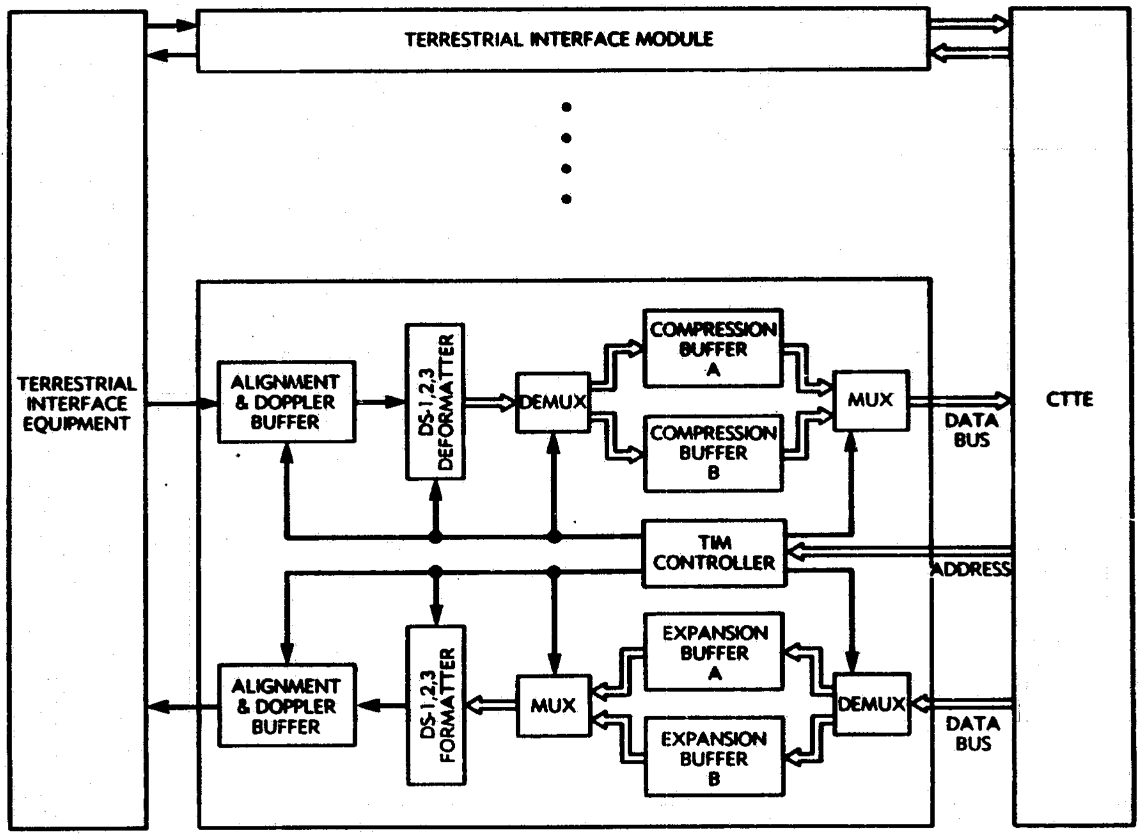

Figure 5-9. Terrestrial Interface Module Block Diagram

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transmission. The data are temporarily stored in a compression buffer and sent to the CTTE at the TDMA burst rate.

The structure and complexity of a TIM vary depending on the type of terrestrial interface equipment used. In addition to the conventional PCM digital interfaces, other special TIMs may be required for a digital speech interpolation (DSI) unit and integrated services digital network (ISDN) interface.

Terrestrial interface equipment consists of analog FDM multiplexers/demultiplexers and PCM converters, as shown in Figure 5-10. A terrestrial equipment arrangement for DSI application is shown in Figure 5-11. A conventional means of converting analog voice channels to the standard TDM-PCM format uses a PCM channel bank, where 24 analog voice channels are converted to one DS-1 signal with a transmission speed of 1.544 Mbit/s. A more economical conversion is accomplished by a transmultiplexer, which accepts two groups or two supergroups and generates one or five DS-1 signals. Future terrestrial networks will increasingly employ digital transmission links with DS-1 (1.544-Mbit/s), DS-2 (6.312-Mbit/s), and DS-3 (46.304-Mbit/s) signals, and will require direct digital interfaces at the earth station. This will simplify the terrestrial network interface and significantly reduce the earth station baseband equipment cost.

5.1.5 TRUNK TDMA PROCESSING MODULES

The hardware and software modules necessary for TDMA processing are summarized in Tables 5-1 and 5-2, respectively.

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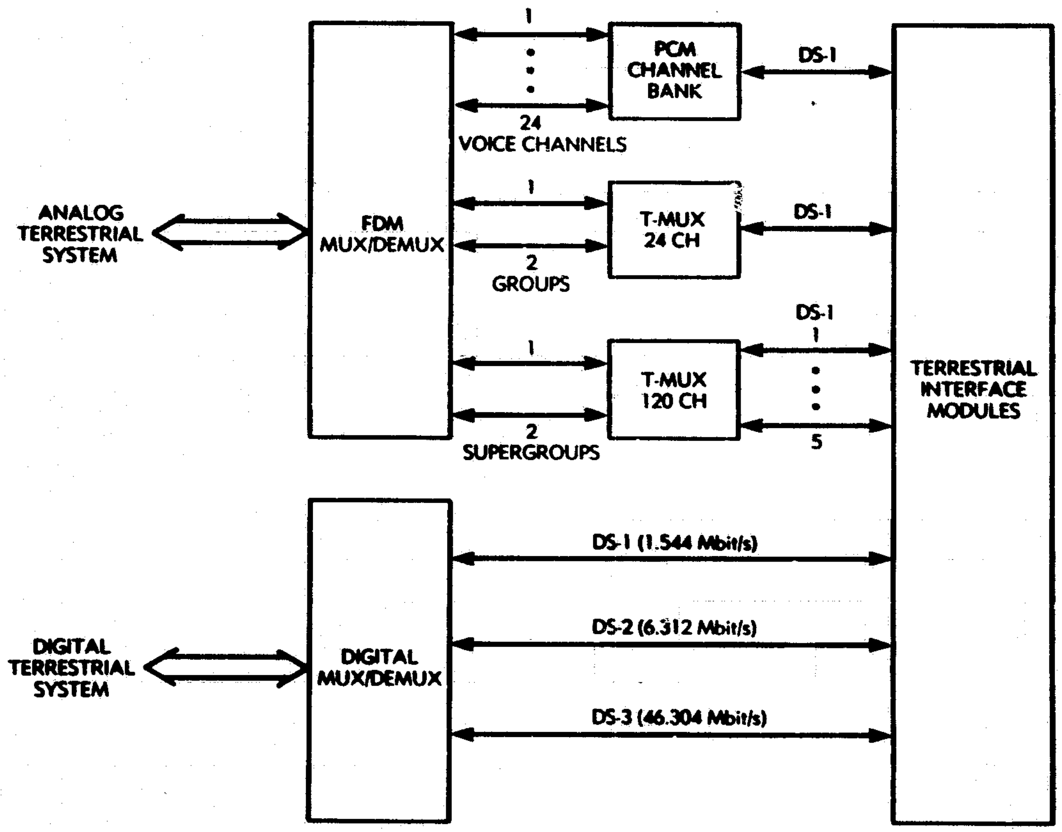

Figure 5-10. Terrestrial Interface Equipment Configuration

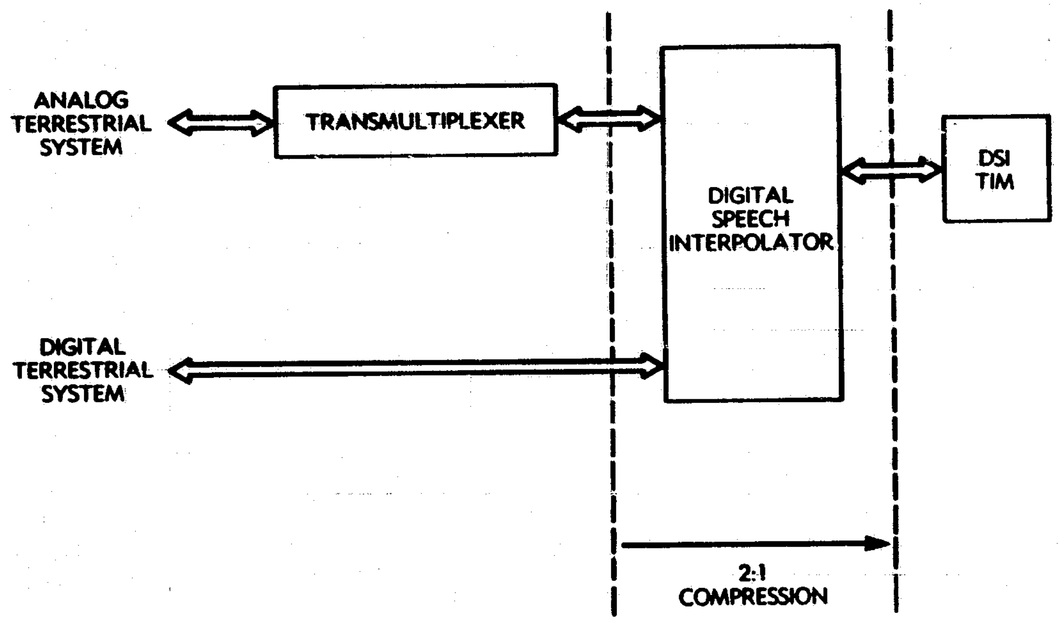

Figure 5-11. Terrestrial Equipment Configuration for DSI

Table 5-1. Trunk TDMA Processing - Hardware Modules

Receive Modules
Diversity Switch Controller
Aperture Generator
Unique Word Detector
Retiming Unit
Descrambler
Receive Timing Generator
Burst Timing Monitor
Burst Demultiplexer
Transmit Modules
Preamble Generator
Scrambler
Transmit Timing Generator
Common Modules
TIM Bus Interface Unit
Oscillator
Control and Display Unit

Table 5-2. Trunk TDMA Processing - Software Modules

Link Control Processing
Acquisition and Synchronization Processing
Orderwire Processing
Receive Processing
Transmit Processing
Traffic Management
I/O Processing
Housekeeping (Monitor, Control, and Diagnostics)

5.2 CUSTOMER PREMISES SERVICE STATION

The customer premises service (CPS) stations have the following characteristics:

a. They are more numerous (200-400 per sector) than the trunking stations
b. They handle a multiplicity of services (voice, data, and video)
c. They use demand assignment of satellite capacity
d. They operate via an on-board baseband processor with separate up- and down-link transmission

The two CPS station sizes are summarized in Figure 5-12. The main differences between the large and small stations are in the antenna sizes and the up-link data rates. Both stations receive a single TDMA down-link burst at 256 Mbit/s using QPSK.

5.2.1 BURST TIME PLAN

RF burst locations and the associated traffic channel positioning within the traffic bursts are embodied in the BTP. The BTP is the graphic or tabular description of the CPS network burst structure. It is stored in computer memory at the MCS and gives the position of all bursts in the CPS network as well as the order of traffic in each traffic burst. Since the current experimental system is based on two different up-link data rates, 128 Mbit/s and 32 Mbit/s, two kinds of BTPs are possible. An example of a station burst time plan is shown in Figure 5-13. It

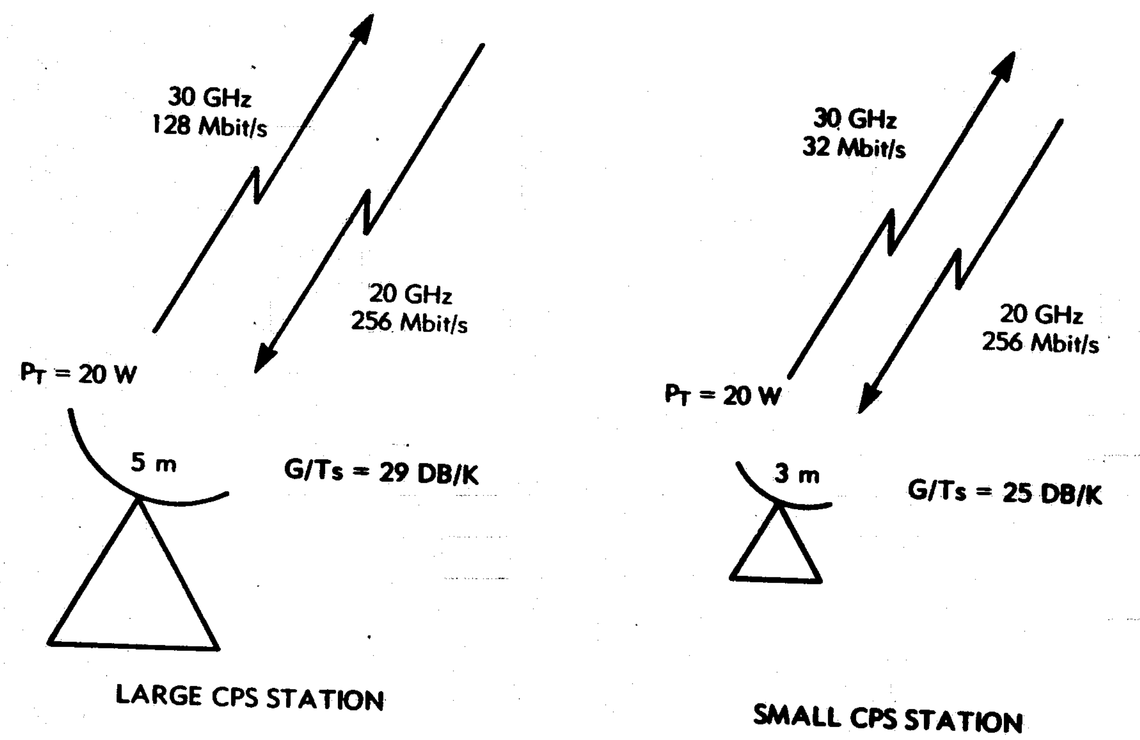

Figure 5-12. CPS Stations

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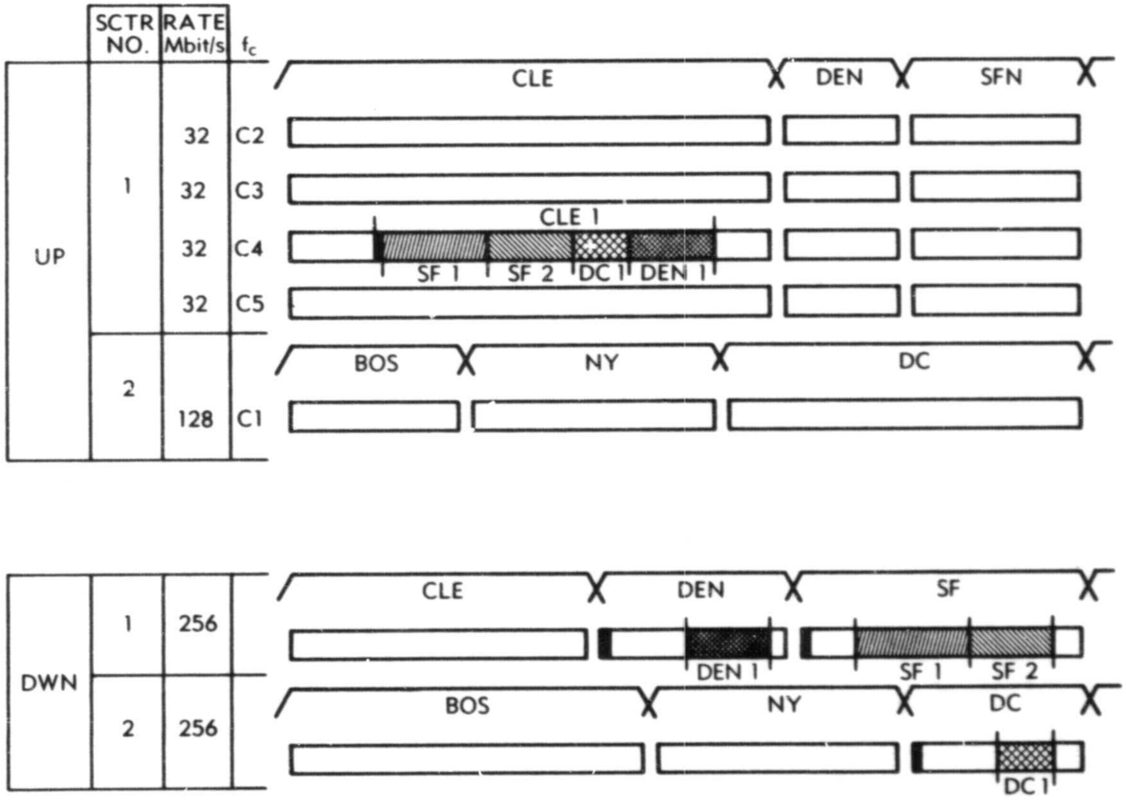


Figure 5-13. Up-link and Down-link Burst Formats

shows the RF image of the up- and down-link traffic bursts for a particular station, CLE1, which has four corresponding stations.

5.2.2 CPS NETWORK LAYERS

From a network point of view, Figure 5-14 summarizes CPS station structure. The figure shows the equipment layers in two CPS stations as well as the associated protocol and interface layers.

The users interface to the CPS station via various kinds of service modules, i.e., TIMs. Each TIM has a distinct hardware and software structure depending on the type of service (voice, video, or data).

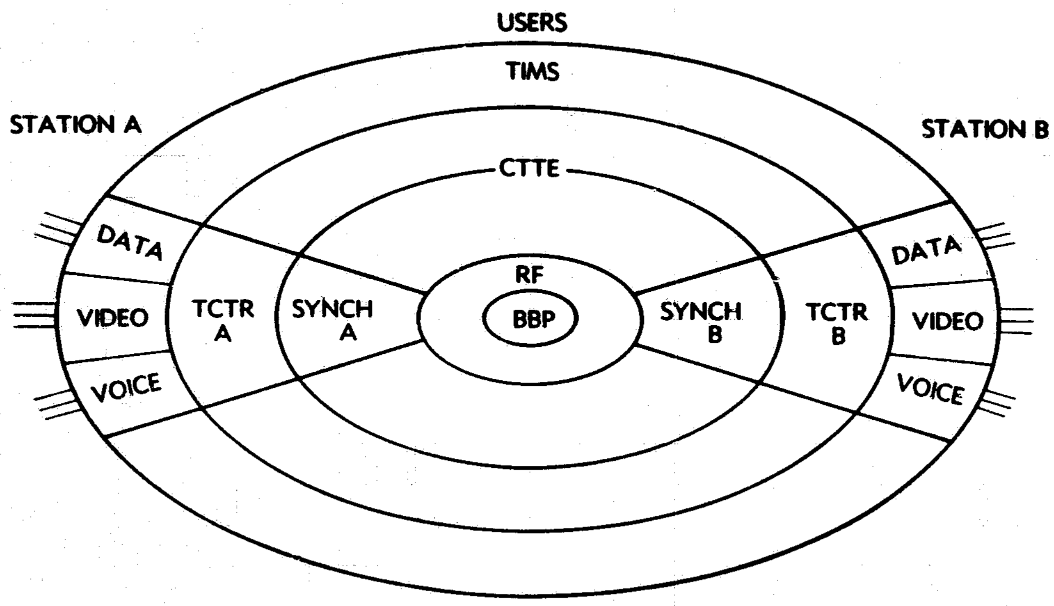
The CTTE consists of two parts:

a. synchronizer
b. traffic controller (TCTR)

The synchronizer keeps the station in sync. It manages burst positioning in the up- and down-links as well as the associated burst synchronization protocols. It does not manage any multiplexing or demultiplexing of up and down traffic, since that is a next-layer function.

The traffic controller has the following functions:

a. Multiplex the transmit data from the TIMs according to the station BTP
b. Process new connect/disconnect requests from own and corresponding TIMs
c. Generate up-link assignment requests to MCS



TIM = TERRESTRIAL INTERFACE MODULE
CTTE = COMMON TDMA TERMINAL EQUIPMENT
TCTR = TRAFFIC CONTROLLER

Figure 5-14. CPS Network Layers

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d. Read and store up-link channel assignment grants from MCS
e. Read and store down-link traffic channel assignments in the received burst on a TIM-by-TIM basis
f. Demultiplex the traffic channels in the down-link burst
g. Drive display
h. Process station-to-MCS orderwire
i. Control compression/expansion buffers

5.2.3 TEST CONFIGURATIONS

It shall be possible to test any single-layer equipment pair by the use of inner-layer simulation equipment. Thus, for example, it shall be possible to test two standalone synchronizers by means of RF and BBP simulation equipment in the laboratory. This implies that it shall be possible for a synchronizer to acquire and remain in sync without an associated traffic controller. (This independent transmit burst positioning is further discussed under CPS synchronizer hardware.)

5.2.4 EQUIPMENT MODULARITY

The equipment in each network layer shall be built in a plug-in fashion. Thus, it shall be possible within 1 hour to replace any synchronizer by an identical unit. Likewise, the TIMs shall be built in a modular fashion to provide both easy replacement as well as parallel user growth.

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5.2.5 CPS SOFTWARE LEVELS

The software levels for the CPS station are shown in Figure 5-15.

5.2.5.1 CPS TDMA Executive

The CPS TDMA Executive (CPSTDMAEX) is resident in each synchronizer. It is the software part of the microprocessor-controlled synchronizer which executes the algorithms necessary to keep the CPS station in sync. Specifically, TDMAEX:

a. Keeps a record of the receive-sync quality based on UW detection of the down-link burst.
b. Takes evasive action in case of burst UW detection failure.
c. Manages the open/narrow aperture states of the UW aperture detector.
d. Executes the receive sync protocols during receive sync acquisition.
e. Executes the transmit-sync protocols during transmit sync acquisition.
f. Decodes and stores all burst position assignments received from the MCS via the down-link burst.
g. Executes the frame down-count during the ordered transition from an old BTP to a new BTP.
h. Issues synchronizer status signals to the next-layer traffic controller.
i. Decodes and implements burst duration in the form of total channels assigned by the MCS.

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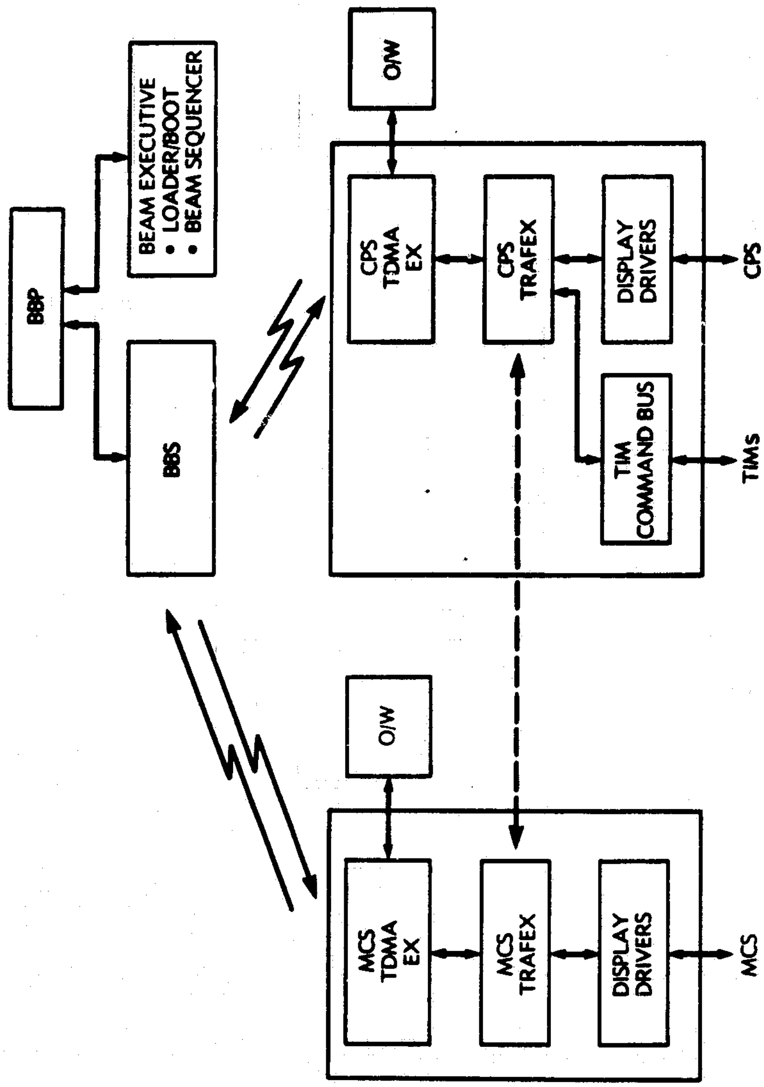

Figure 5-15. CPS System Software Levels

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j. Generates burst countdown signal during transition between any old and new order-of-traffic (OOT) for use by traffic controller.

It is important from the standpoint of reliability to limit the TDMAEX software only to those functions necessary to prevent synchronizer "crashes." A failure to position TIM traffic into the proper channels within a transmit burst can only affect TIM traffic in the corresponding stations; it does not have any destructive effects on transmit bursts from other stations. For this reason the TDMAEX contains no data on the channel-by-channel ordering of TIM traffic. However, to generate the carrier on-off signal (CRON) for the modulator the TDMAEX must not only decode and implement the transmit burst position from the MCS but it must also decode and implement the transmit burst duration implied by the total number of channels assigned to the CPS station in question.

5.2.5.2 CPS Traffic Executive

The CPS Traffic Executive (TRAFEX) is the software part of the microprocessor-controlled traffic controller (TCTR). The TRAFEX interfaces with

a. the synchronizer status lines
b. TIMs
c. displays
d. operator station.

On the synchronizer side the TRAFEX has the following functions:

a. Read and interpret synchronizer status signals
b. Read/store/implement TIM-to-channel translation tables in own transmit burst as well as in received down-link mono-burst according to current BTP
c. Calculate/formulate channel assignment requests for transmission to MCS traffic executive, resident of the MCS station
d. Interpret re-assignment downcount generated by synchronizer during transitions between old and new BTPs
e. Order traffic from TIMs in compression buffers according to current BTP

On the TIM side the TRAFEX has these functions:

a. Read TIM status (on-line, off-line, TIM type)
b. Receive and process TIM channel requests
c. Handle TIM-to-TIM handshaking between stations
d. Execute SYSGEN program at station start-up (detect, classify, list all TIMs)
e. Demultiplex data in receive expansion buffers on a channel-by-channel basis according to current BTP

5.2.6 CPS STATION HARDWARE

The CPS Station Hardware consists of:

a. Antenna and Pedestal
b. RF Terminal
c. Modem
d. Synchronizer
e. Traffic Controller
f. Terrestrial Interface Modules

5.2.6.1 CPS RF Terminal

The elements of the CPS RF terminal are blocked out in Figure 5-16. A step-track mechanism is used to keep the antenna pointed by means of the beacon from the satellite. The elements necessary to distinguish between the vertical and horizontal polarization, associated with specific spot beam sectors, are not included.

5.2.6.2 CPS Synchronizer

This is probably the single most important piece of equipment for reliable CPS network operation. If any synchronizer "crashes" and transmits erroneous bursts at incorrect burst positions in violation of the BTP, there may be disastrous collisions with up-link bursts from other CPS stations. As a result all the network portions associated with a particular TDMA up-link carrier may fail completely. For this reason, the

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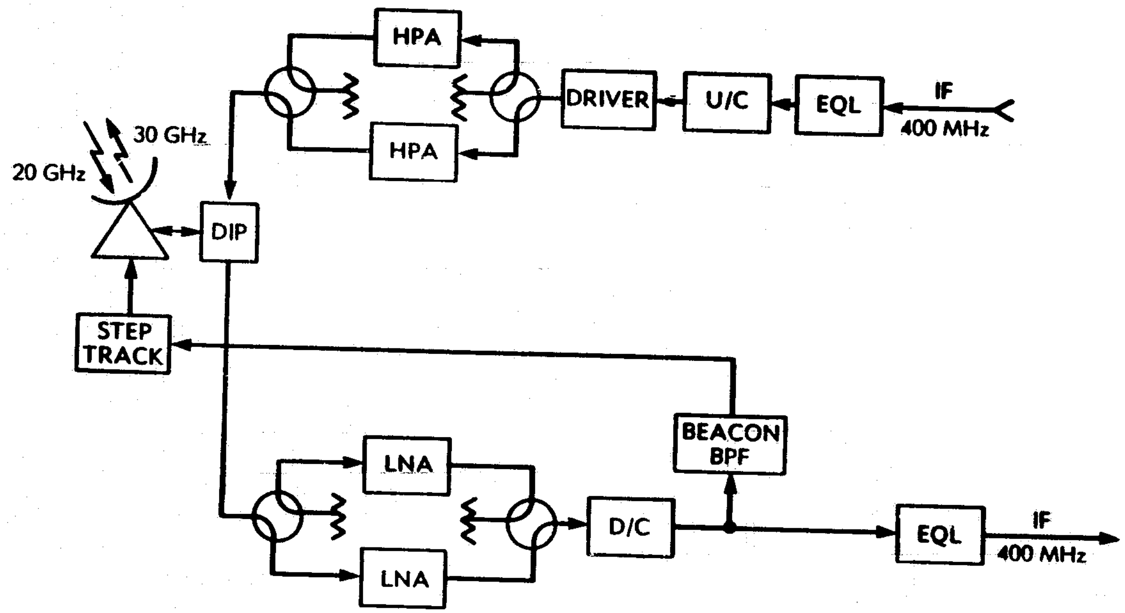

Figure 5-16. CPS RF-Terminal

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synchronizer must be a fail-safe piece of equipment with tightly controlled and tested performance.

The single supreme function of the synchronizer is to keep the transmit burst synchronized in accordance with the current BTP.

The basic blocks of the synchronizer are shown in Figure 5-17.

There are three basic ingredients necessary for proper steady-state synchronization of the CPS transmit burst:

a. Detect the UW in the down-link burst to derive a transmit time base and identify/decode the position commands from the MCS.
b. Read/store/implement the position commands on the orderwire from the MCS.
c. Measure and count down the time offset from down-link UW arrival until proper transmit burst release.

In addition to these functions the synchronizer microprocessor also controls the up- and down-link activation of FEC as well as modem Hi/Low Data Rate.

The use of the aperture loop in monoburst detection is illustrated in Figures 5-18 and 5-19. Due to on-board baseband processing there is only one single burst to be detected by all stations in the Cleveland dwell area. Presumably there is no possibility of erroneously locking onto a burst associated with another dwell area because the stations in the Cleveland dwell area cannot "see" the down-link RF intended for other dwell areas. This fact is illustrated in Figure 5-18, which also shows the aperture overlapping the last symbol of the received Unique Word in the down-link burst.

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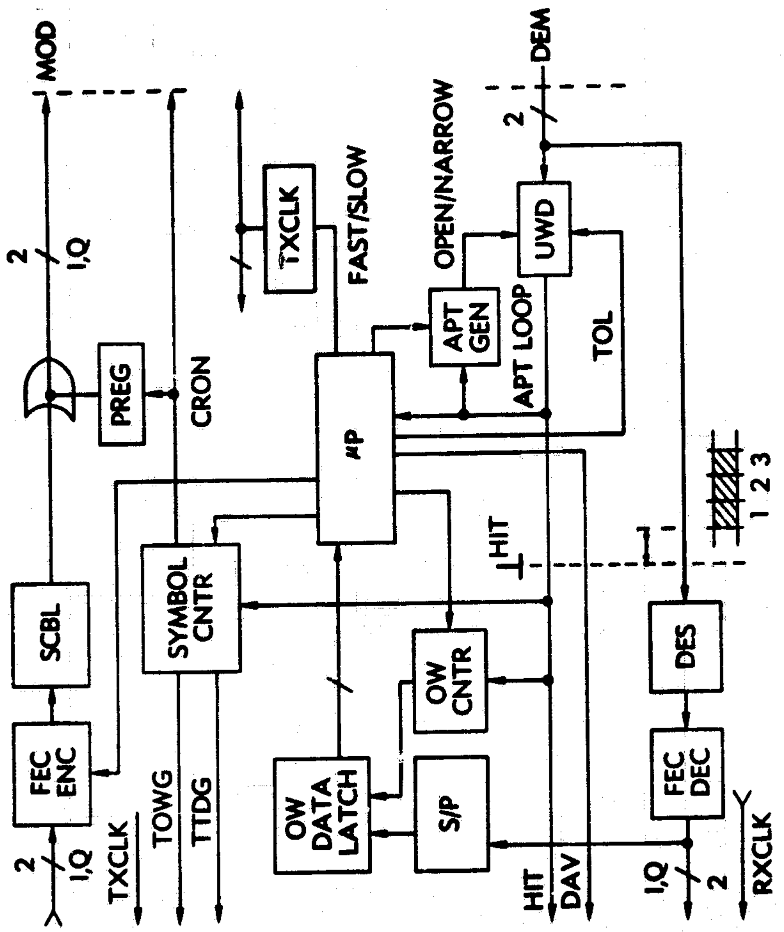

Figure 5-17. CPS Synchronizer

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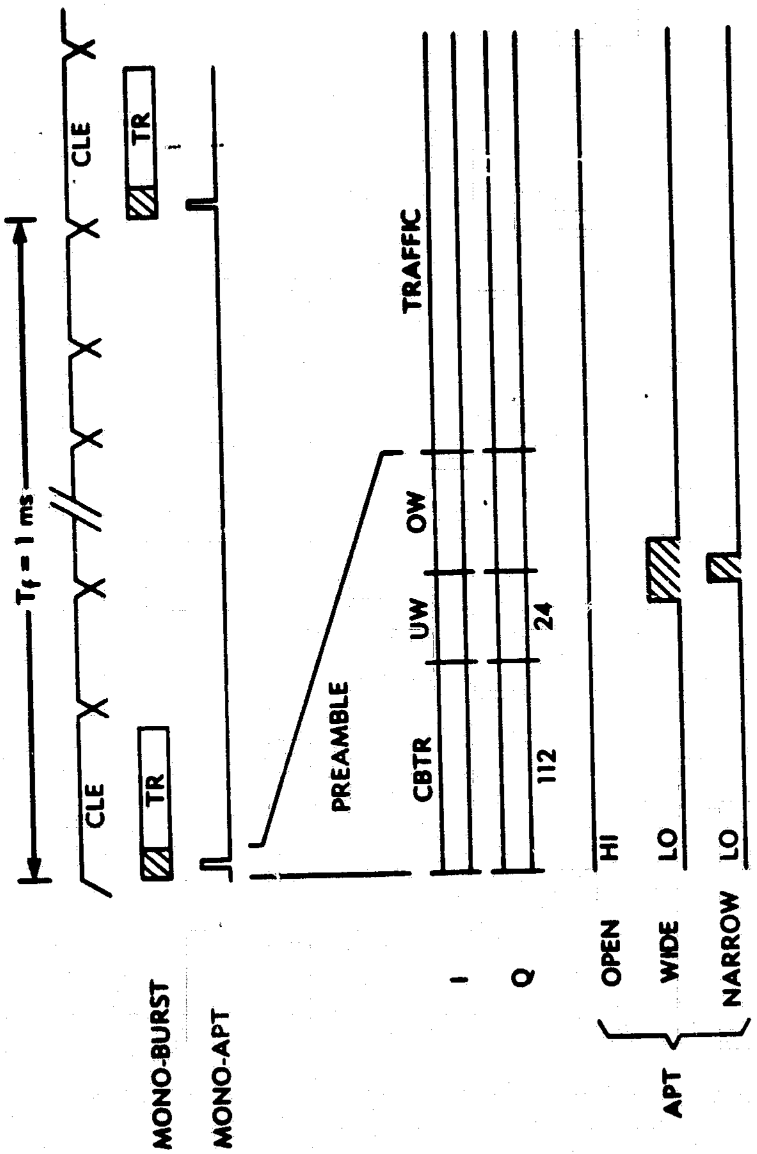

Figure 5-18. Monoburst Detection

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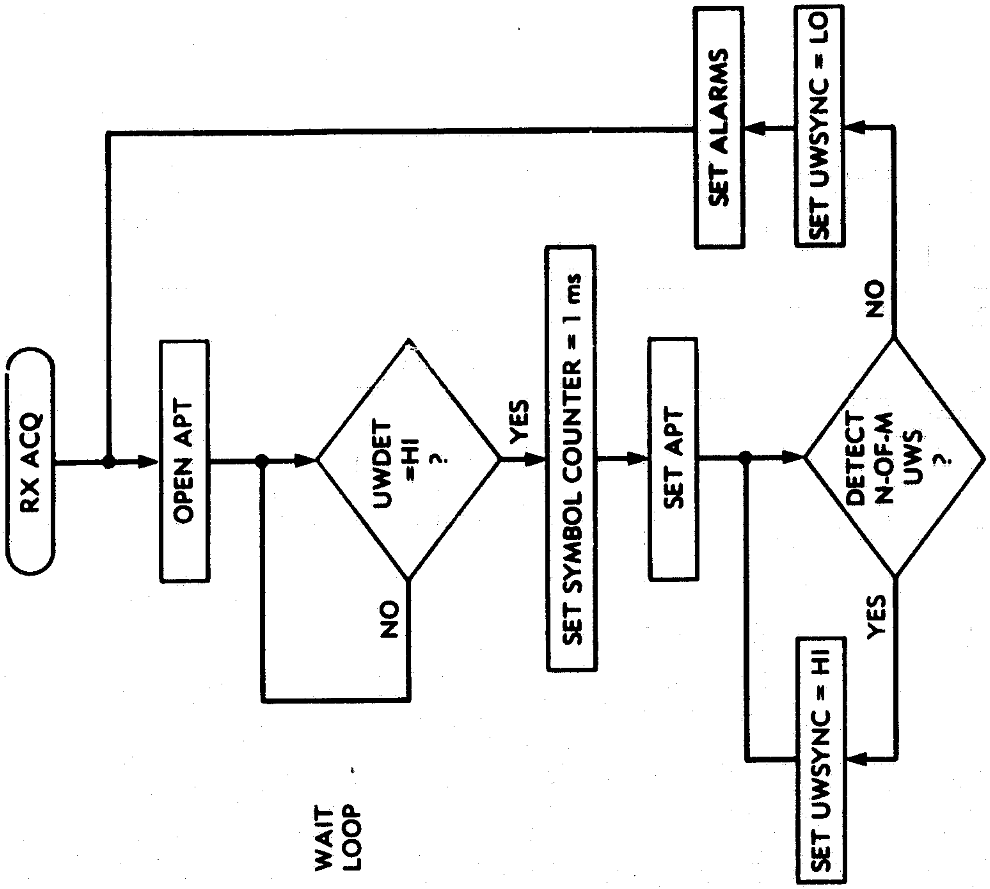

Figure 5-19. Monoburst Detection Algorithm

The burst UW detection algorithm is detailed in Figure 5-19. The values of M and N in the N-of-M criterion is to be determined. The application of bit error tolerance in UW detection is also to be determined (e.g., high tolerance equals 7 bit errors; low tolerance equals 3 bit errors).

On the receive side the synchronizer, in addition to P, Q data and clock, also provides the UW Hit signal to allow demultiplexing of data relevant to Traffic Controller operation. In addition, the Data Valid signal (DAV) "tells" the Traffic Controller when the UW Hit may be used for valid demultiplexing of the P, Q data.

On the transmit side, the synchronizer uses two signals, TOWG (i.e., Transmit Order Wire Gate) and TTDG (i.e., Transmit Traffic Data Gate), to "tell" the Traffic Controller when it "reads" either the transmit orderwire or the transmit compression buffer.

In summary, the synchronizer:

a. Provides remote control (by the MCS) of the CPS transmit burst position
b. Does not distinguish order-of-traffic sequences within the individual transmit or receive channels (a TCTR function)
c. Does not request or release traffic channels in the transmit burst (a TCTR function)

5.2.6.3 Terrestrial Interface Modules (TIMs)

The CTTE/TIM data paths are shown in Figure 5-20. Each TIM consists of two parts:

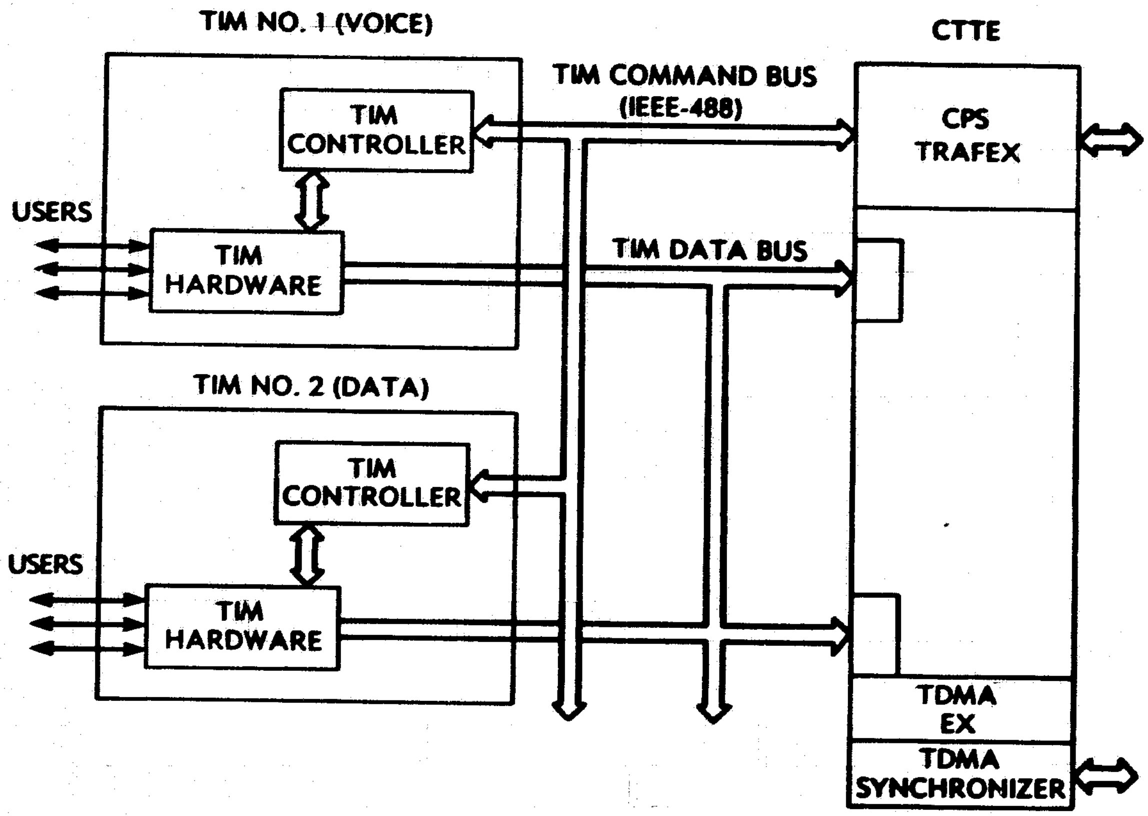

Figure 5-20. CTTE/TIM Data Paths

a. TIM controller (a microprocessor with service dependent software, called TIMEX)
b. TIM Hardware (service-dependent circuits)

All TIMs are interfaced to the Traffic Controller in the CTTE via a common bus, TIMBUS. The TIMBUS has a medium-speed command bus for handshaking between TIMEX and TRAFEX. It also has a high-speed parallel bus for bulk traffic data transfer between the TIM hardware and the CTTE compression/expansion buffers. A convenient command bus structure is based on the IEEE-488 (GPIB) bus, although the off-the-shelf ICs for this standard bus are probably too slow.

A specific example of a Data TIM is given in Figure 5-21. The associated transmit RAM operation performs the typical ping-pong operation between the two parallel compression RAMs. When one RAM is being emptied at the high transmit data rate, the other RAM is being loaded with data from the TIMs.

5.2.6.4 T2/DSI/TIM

The network configuration of the T2/DSI TIM is outlined in Figure 5-22.

This TIM can be used for two specific purposes:

a. Interface with a standard Bell System D2 channel bank to carry 96 analog voice channels using DSI
b. Interface with a Bell Systems M12 multiplexer to process a 96-channel T2 carrier (6.312 Mbit/s)

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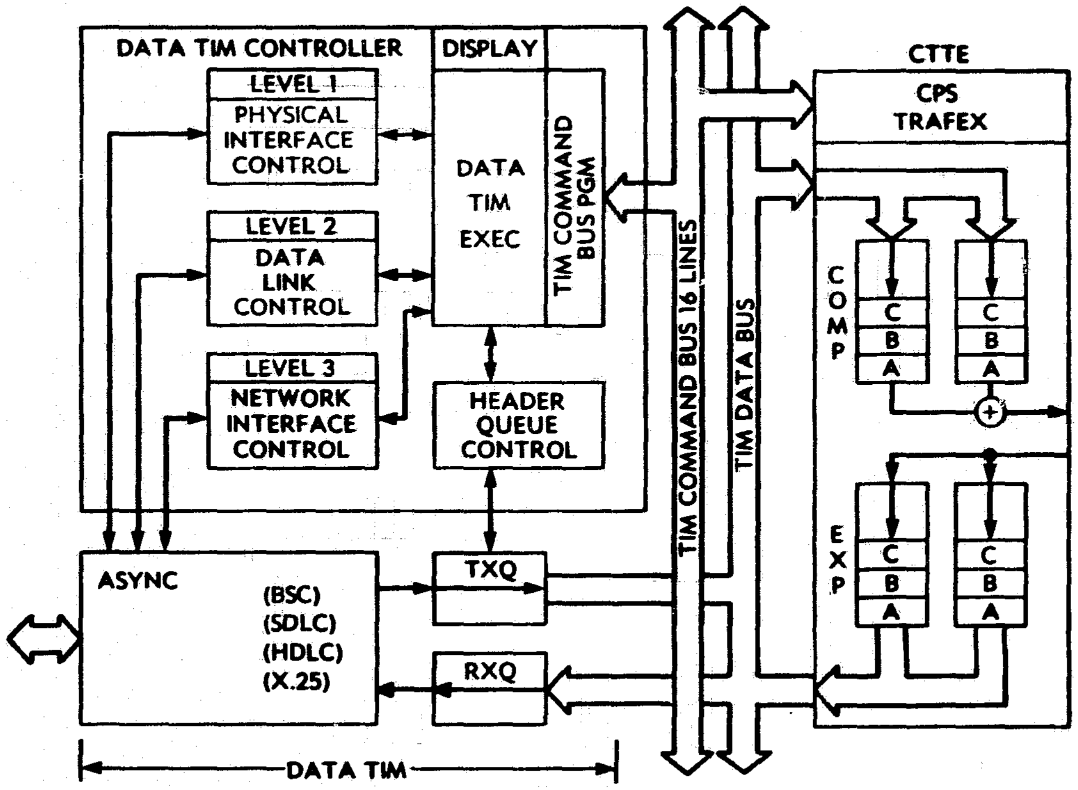

Figure 5-21. Data TIM

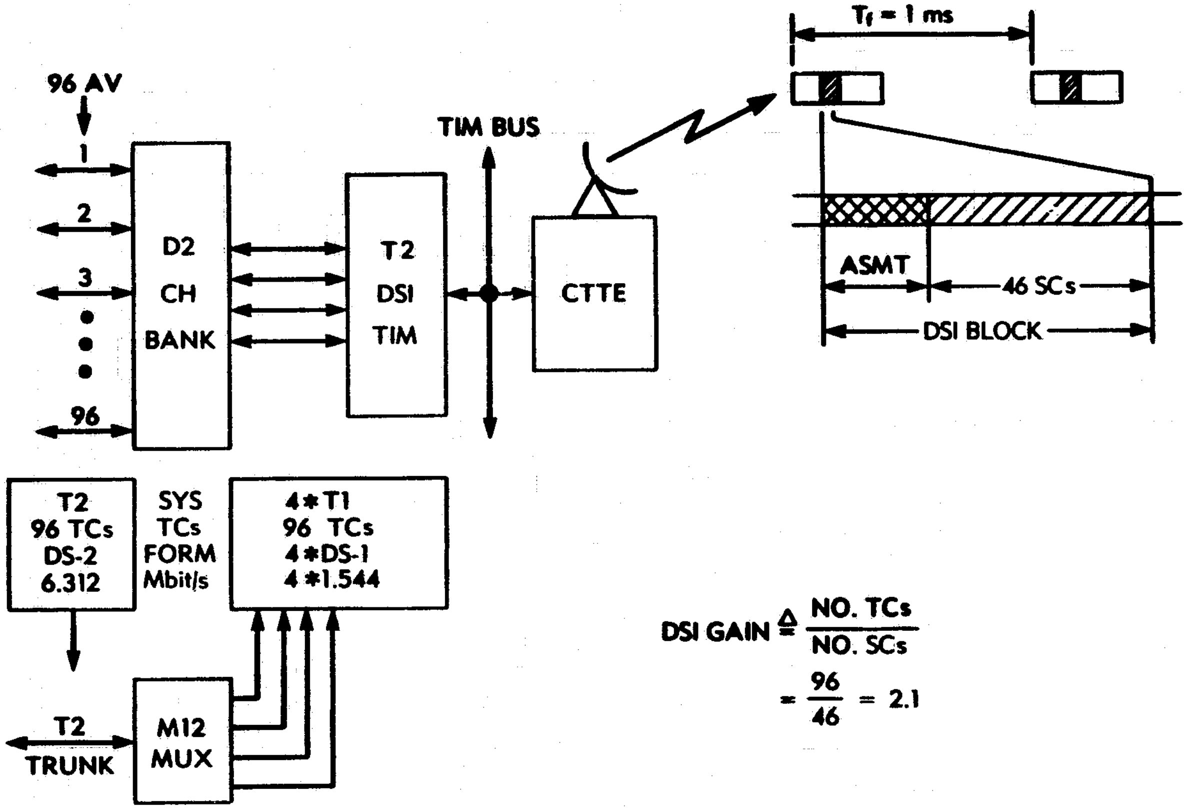

Figure 5-22. T2 DSI TIM Interface

DSI is a standard technique used to increase the voice-carrying capacity of the satellite. When a terrestrial channel (TC) is quiet (approximately 40 percent of the time) the up-link satellite channel (SC) is given to another voice-activated terrestrial channel. As shown in Figure 5-23, the 96 voice channels on the T2 carrier would only require 46 PCM satellite channels, a considerable saving.

In the D2 case there is no restriction on the terrestrial channel networking. For example, for simplicity there may be no signaling and switching done by the TIM or by the on-board BBP. For example, 4 TCs may be fixed-assigned to a permanent destination CPS station, 9 TCs to a different CPS station, etc. On the other hand, signaling and switching may be included in the CPS network so that either the TIM or the on-board switch may switch a terrestrial channel to different destination CPS stations at different points in time.

The same remarks do not apply to the T2-trunk case. All 96 T2 voice channels would probably be fixed-assigned to a specific destination CPS station. The reason is that the DS-2 signal format used by the T2-carrier system interleaves the bits from different voice sources so that switching of the individual voice samples is rather complicated at the T2-carrier level.

5.2.6.5 CBX TIM

The network configuration for the CBX TIM is outlined in Figure 5-24. This TIM allows remote interconnection of private CBXs via the satellite.

As far as the CBX is concerned, the satellite trunks are similar to ordinary terrestrial trunks to a local office.

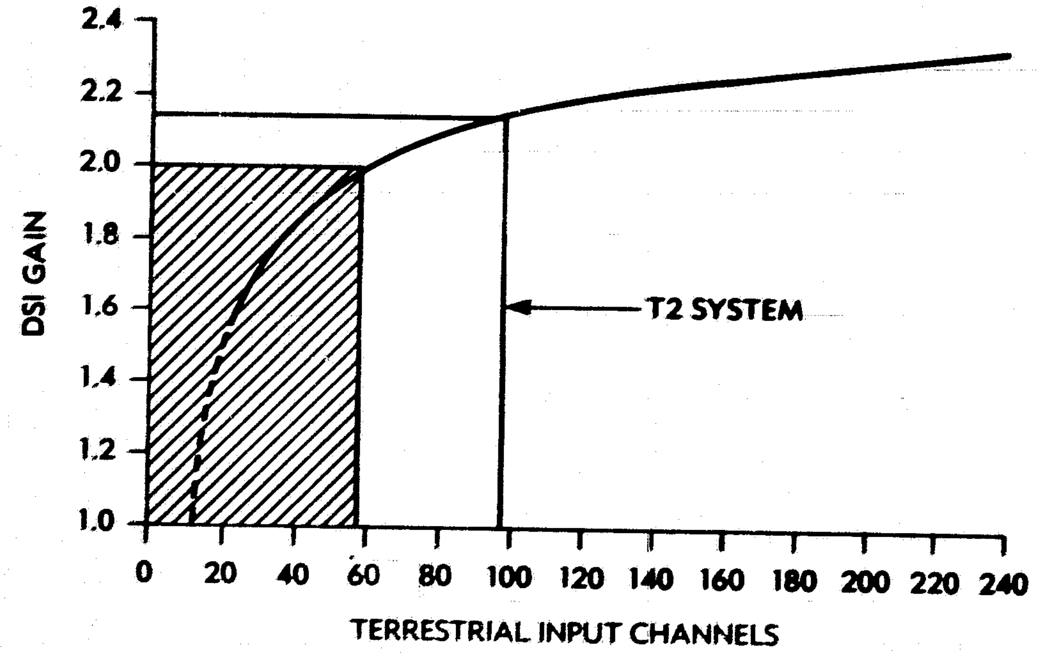

Figure 5-23. DSI Gain Curve

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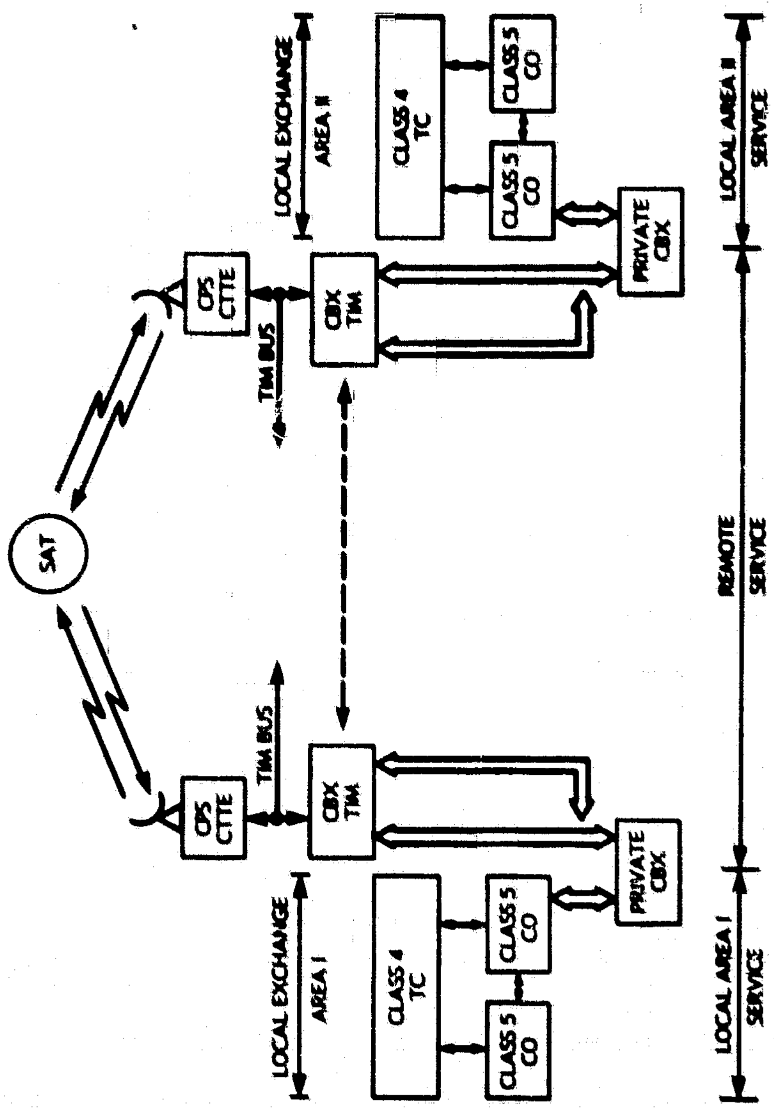

Figure 5-24. CBX TIM Interface

The CBX TIM handles all the standard switching functions associated with the trunk office:

a. alerting
b. attending
c. call processing
d. busy testing
e. supervision
f. switching.

The stippled line in Figure 5-24 implies that there is an inter-TIM software level of which the call processing takes place.

5.2.6.6 X-25 TIM

The X-25 TIM is the interface between the public packet-switched networks (in the U.S.: Telenet, TYMNET, Graphnet, Uninet; in Canada: Datapac). The X-25 TIM handles the standard X-25 protocol defined for packet-switched networks. This is illustrated in Figure 5-25.

5.2.7 CPS TDMA PROCESSING MODULES

The hardware and software modules necessary for TDMA processing are summarized in Tables 5-3 and 5-4, respectively.

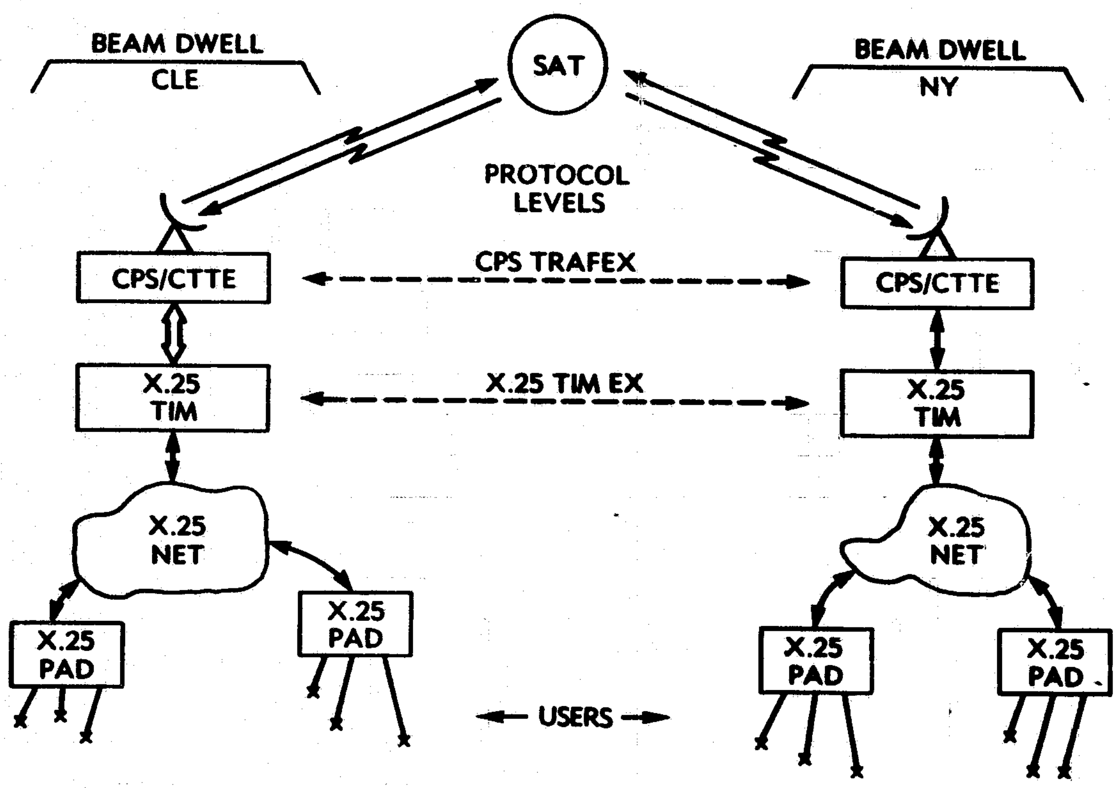

Figure 5-25. X.25 TIM Interface

Table 5-3. CPS TDMA Processing - Hardware Modules

Receive Modules
Aperture Generator
Unique Word Detector
Retiming Unit
Descrambler
FEC Decoder
Receive Timing Generator
Burst Demultiplexer
Transmit Modules
Preamble Generator
Scrambler
FEC Encoder
Transmit Timing Generator
Common Modules
TIM Interface Unit
Oscillator
Control and Display Unit

Table 5-4. CPS TDMA Processing - Software Modules

Acquisition and Synchronization Processing
Orderwire Processing
Receive Processing
Transmit Processing
Call Processing
Traffic Management
I/O Processing
Housekeeping (Monitor, Control, and Diagnostics)

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5.3 MASTER CONTROL STATION

The MCS performs all the necessary control and processing functions for the 30/20-GHz experimental system. Status and control data exchange between network stations and the MCS is accomplished via orderwire channels, and the spacecraft communications payload is controlled through both orderwire channels and a TT&C data link. Figure 5-26 is a system block diagram of the MCS.

The network controller (NC) processes orderwire and system monitoring data and sends network control data to participating earth stations. The NC also monitors local subsystem operation and is capable of self-diagnosis, fault detection and isolation, and automatic redundancy switch-over to achieve virtually no system down-time. In an operational system, additional protection must be provided by a backup MCS at a separate location to avoid system outage.

Local terrestrial traffic channels are processed by a local traffic processor (LTP) which shares high-speed burst processing hardware with the NC. Since necessary timing and channel assignment data for traffic processing are readily available in the NC, the LTP design is relatively simple. The MCS can experiment with various terrestrial network interfaces in a satellite loopback mode or in conjunction with other earth stations in different beam zones.

Experimental system operation is supported by three operations centers: the mission operations center (MOC), network operations center (NOC), and experiment operations center (EOC). The major functions of the MOC are spacecraft operation and payload control, such as TT&C data processing, spacecraft attitude control, thermal control, and stationkeeping maneuvers. The NOC

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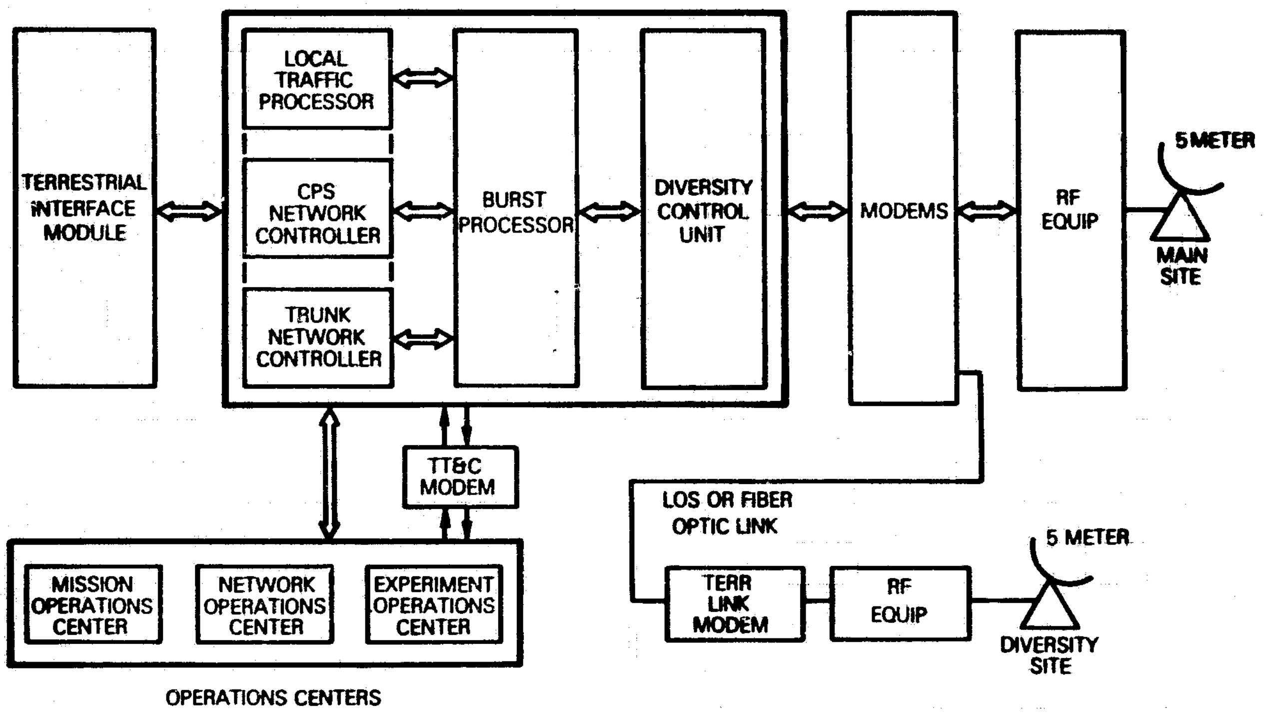

Figure 5-26. Master Control Station

collects and analyzes a large amount of station and BBP status data, which are not time critical, and supervises overall network operation by interacting with the trunk and customer premises services (CPS) NCs. A variety of service and technology experiments are conducted under the EOC directives, and experimental results are analyzed, summarized, and reported for assessment of an operational system. The three operations centers communicate interactively to accomplish the objectives of the experimental system.

5.3.1 TRUNK NETWORK CONTROLLER

The trunk NC is responsible for time-critical data processing such as acquisition, synchronization, power control, and station alarms. The response time upon receiving station status must be of the order of 100 ms to 1 s. Non-time-critical data, as well as detailed system analyses and data base generations, are processed by the NOC. The functions of the network controllers and operations center are summarized in Figure 5-27.

The trunk NC consists of four orderwire processing units, an onboard acquisition and synchronization unit (ASU), and a link monitor subsystem (LMS). Figure 5-28 is a block diagram of the trunk NC. The four orderwire processors perform the following tasks:

a. <u>channel assignment processor (CAP)</u>: channel assignment processing,
b. <u>acquisition and synchronization processor (ASP)</u>: open-loop acquisition assistance and transmit timing error correction,

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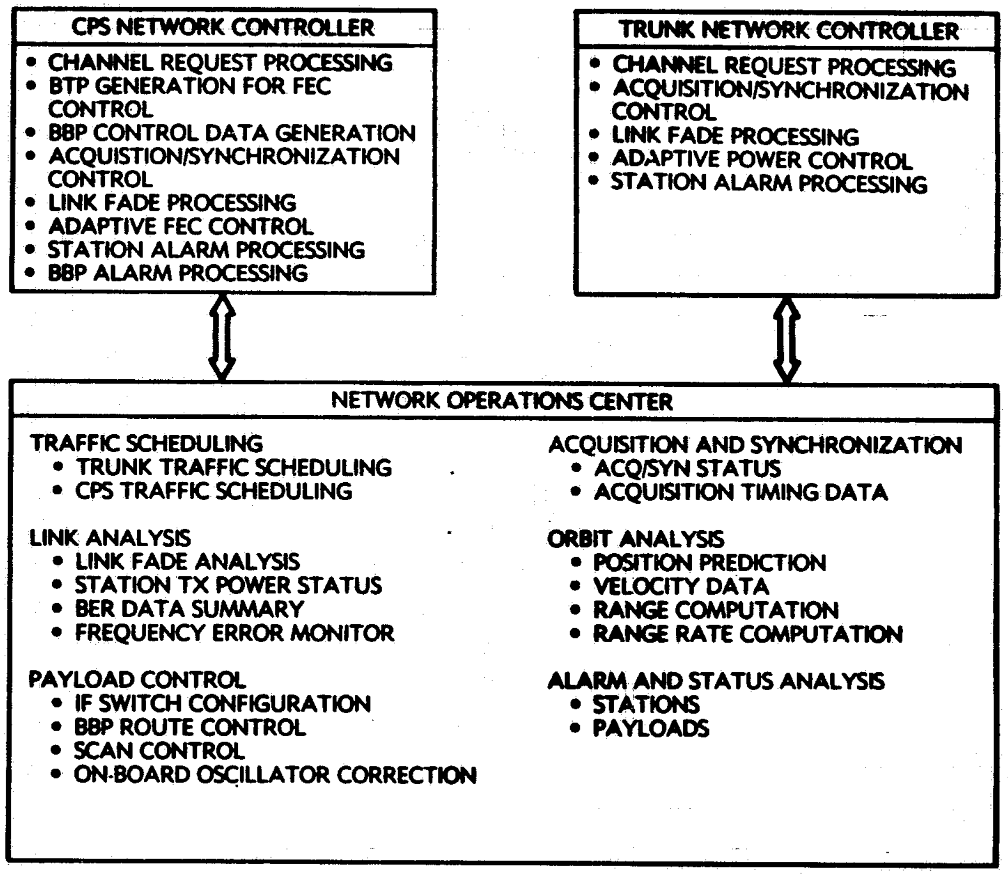

Figure 5-27. Network Control Processing Functions

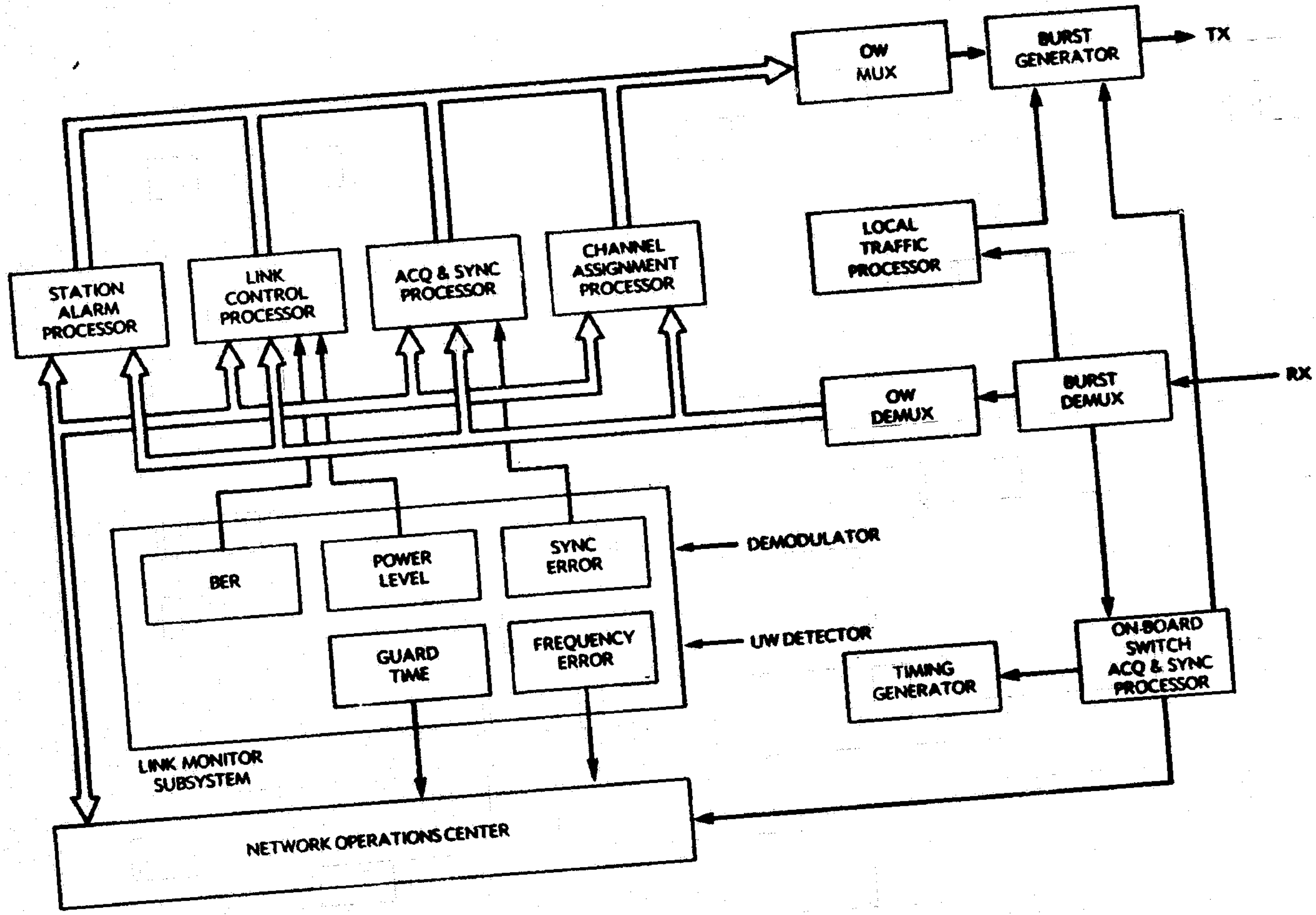

Figure 5-28. Trunk Network Controller

c. <u>link control processor (LCP)</u>: rain fade detection and transmit power control, and

d. <u>station alarm processor (SAP)</u>: station status data processing and control.

The LMS monitors the BER, burst power level, synchronization accuracy, guard time, and frequency error of each orderwire burst. The monitored data are supplemented by the station orderwire data in determining accurate link fades and transmit timing errors. The ASU performs onboard switch-state acquisition and synchronization and supplies frame reference timing to the NC. It also measures long-term drift of the onboard oscillator against a high-stability master clock. The measured phase errors are processed at the NOC, and a correction value is sent to the satellite via the TT&C link.

5.3.1.1 Channel Assignment Processor

A BTP is updated once every 66 seconds in the trunk network and does not require immediate processing of channel request data. The CAP reformats and transfers the request data to the NOC and controls duplicated assignment data transmission to the respective beams.

5.3.1.2 Acquisition and Synchronization Processor

Each trunking station is preassigned 32 consecutive frames in a control frame for orderwire transmission, and the MCS detects orderwire bursts and measures their timing errors relative to its aperture window timing. The transmit timing error is computed by averaging the 32 measurements and sent to the trunking station to update its transmit timing once every control frame (about 1 second). The ASP is dedicated to perform this function for all network stations; its processing flow is shown in Figure 5-29.

An orderwire burst aperture is initially completely open for 1.333 μs to accommodate the worst-case ranging accuracy of ±200 m. If no orderwire bursts are detected during the open-aperture state, the ASP assumes that the corresponding trunking station is inactive and sends open-loop acquisition data to the station. When acquisition orderwire bursts are detected, the station acquisition/synchronization status is set to "acq", and the timing error is corrected by feedback control. The orderwire bursts following the timing error correction should be located within a few symbols of the nominal position of an orderwire burst slot. If the timing error is no more than ±4 symbols, the station is in the "sync" state and instructed to transmit traffic bursts. Concurrently, the orderwire burst aperture width is narrowed to 16 symbols. In steady-state synchronization, the timing error should not exceed ±4 symbols. If it does exceed this value, a detailed analysis is performed in the NOC to identify the problem and instruct the station to disallow traffic burst transmission when it is excessively large. Additional timing information is also available in the station status and alarm data of orderwire bursts.

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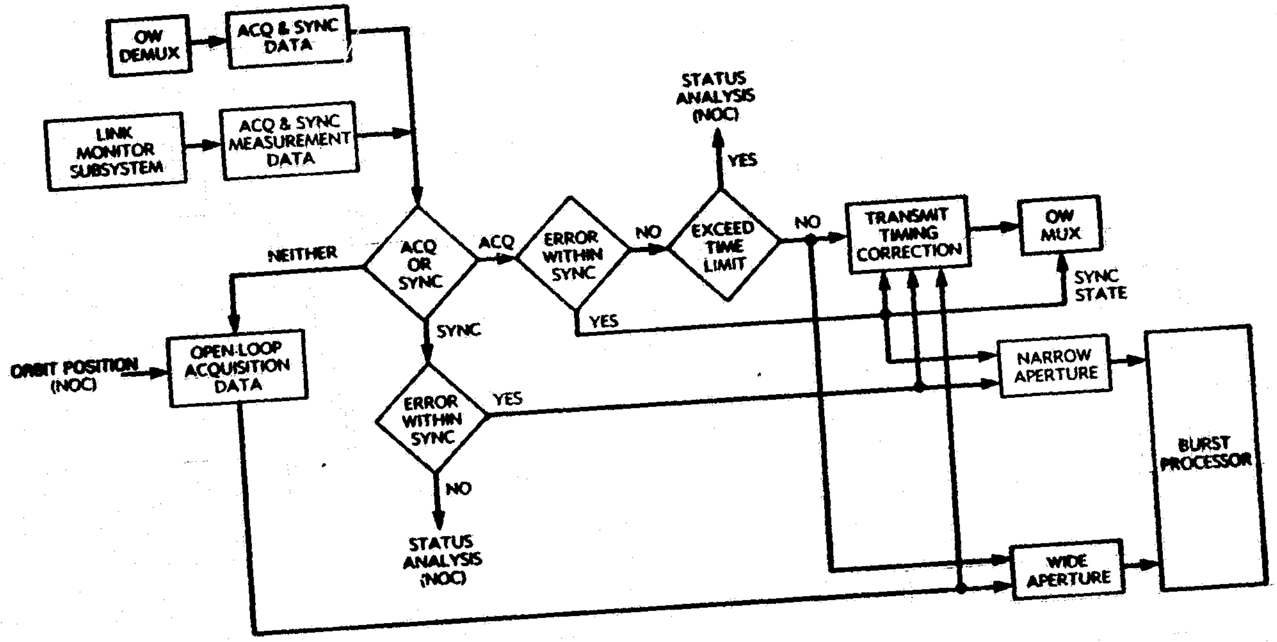

Figure 5-29. Trunk Acquisition and Synchronization Processing

5.3.1.3 Link Control Processor

Rain fade data are collected at each trunking station by measuring beacon power and BER, and the data are sent to the MCS via orderwire bursts. A link margin control procedure is shown in Figure 5-30. The LCP creates a rain fade data file from the orderwire data and LMS data and computes the up-link and down-link fades for every active trunking station. Discrepancies among measurement data, if any, are further analyzed and resolved at the NOC. For an up-link fade, the station's transmit power is increased up to 10 dB. A down-link fade is controlled by adjusting the satellite transmit power level. The LCP also monitors and controls the local diversity switching unit by comparing the down-link fade levels of the main diversity terminals.

The effect of rain fade on the channel BER must be minimized by updating the fade control data once every control frame. Since the worst fade rate is about 1 and 0.5 dB/s for 30- and 20-GHz links, respectively, a combined link degradation of 5.3 dB is expected during the link margin control process in the worst case.

5.3.1.4 Station Alarm Processor

The SAP communicates with other NC processors to detect any abnormal station operation. There are three major station alarms:

a. BER,
b. UW loss, and
c. orderwire message.

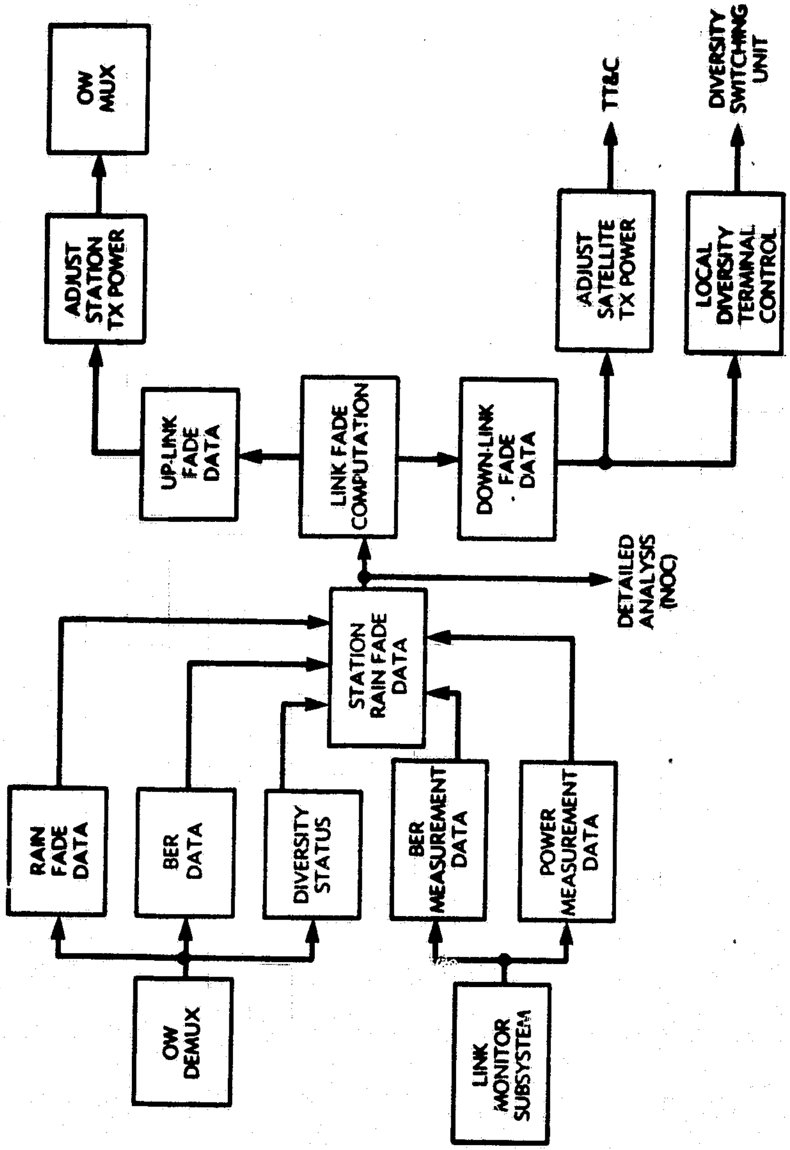

Figure 5-30. Link Margin Control Procedure

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The BER threshold is set to 10^{-6}, and any burst with a higher BER is reported to the MCS. The UW loss alarm is set when the unique word of a trunking station burst is missed for 10 consecutive frames. The third alarm (c) is used when a station is not able to decode orderwire messages correctly. The SAP analyzes these alarms as well as other status data and sends proper commands to the trunking station. The outgoing control messages include the following:

a. stop burst transmission,
b. adjust transmit power level, and
c. execute a new BTP.

In addition to these messages, the NC exchanges the acquisition/synchronization status, availability of terrestrial data ports, diversity terminal condition, and backup MCS operation if any with individual trunking stations.

5.3.2 CPS NETWORK CONTROLLER

A CPS network controller is shown in Figure 5-31. The functions of the CPS NC are quite similar to those of the trunk NC. However, the CPS NC also provides the following additional processing capabilities:

a. <u>BBP route control processor (RCP)</u>: computations of control memory contents of the baseband processor (BBP) route controller and BFN controller, and
b. <u>BBP alarm processor (BAP)</u>: BBP status/alarm processing and control

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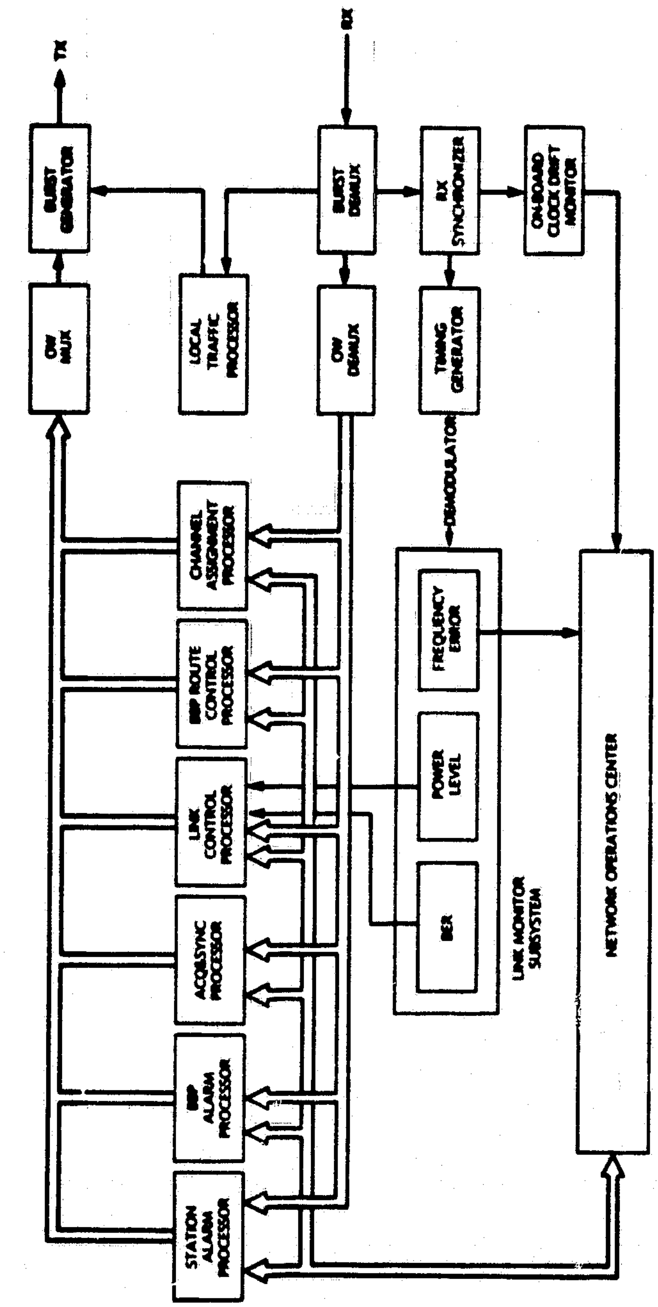

Figure 5-31. CPS Network Controller

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The CPS NC controls not only earth station operation but also on-board hardware for burst detection and channel routing.

The MCS receives and transmits only one burst per frame, and its processing mechanism is relatively simple. However, extensive orderwire data processing is required to control the BBP controller and station transmit timing on the satellite.

5.3.2.1 Channel Assignment Processing

In the CPS network, the link degradation due to rain fades is compensated by FEC coding at earth stations as well as on the satellite. If the station data throughput is kept constant during a heavy rain fade, the traffic burst length must be expanded to accommodate FEC overhead. This requires a rapid deployment of a new channel assignment over the entire network. For this purpose, a short channel assignment rate of 1 second (or one control frame) is selected for the CPS system. An assignment change also affects the route control unit of the onboard BBP, and a systematic channel assignment procedure must be implemented in the CPS NC. Figure 5-32 illustrates the processing flow for channel assignment.

As in the trunk system, the LCP creates a link fade data file for individual CPS stations and generates fade control data. If a down-link beam experiences fading, on-board FEC coding must be applied for that dwell area. For an up-link fade, CPS stations employ coding, and the coded bursts are decoded on the satellite. The effect of FEC coding in either link results in the construction of a new BTP.

A rapid channel reconfiguration requirement also stems from the generic nature of CPS networks, i.e., a large number of

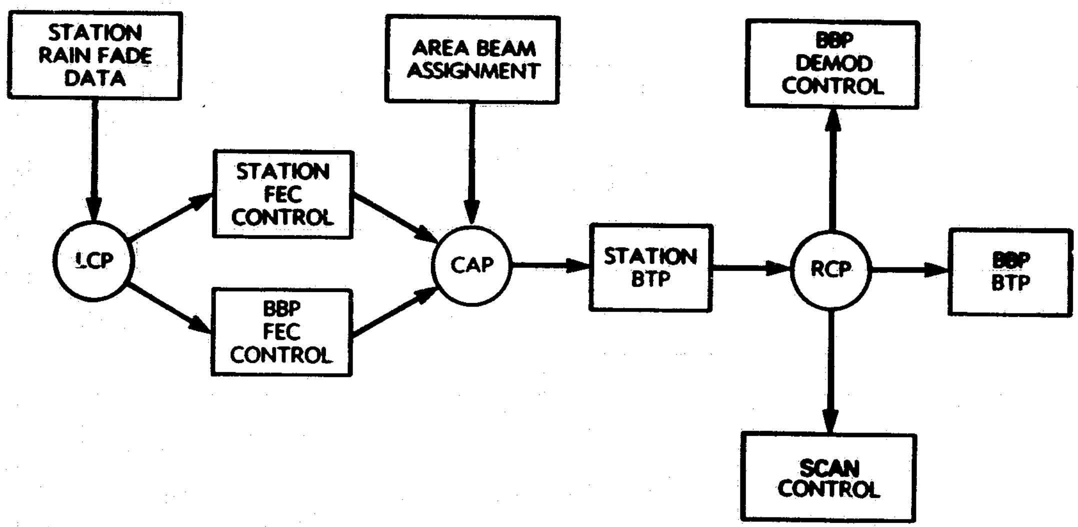

Figure 5-32. Processing Flow for Channel Assignment

small users. Channel activities of individual users change rather frequently, and a demand-assigned system provides an efficient utilization of available resources in a time-varying environment.

The experimental system employs two stages of processing steps to implement efficient demand-assignment operation. The NOC allocates the transmit and receive time segments for dwell areas in the two scanning beam sectors based on a projected traffic plan or an actual capacity demand. Extra capacity is distributed to each dwell area according to the forecasted rain activity in that area and will be used for rain margin control and future traffic growth. The CAP performs burst scheduling and generates a BTP which is consistent with the dwell beam assignment generated by the NOC. Processing steps of the CAP are shown in Figure 5-33. When a channel request for some dwell area exceeds the presently assigned capacity, new requests are temporarily queued, and the NOC initiates global traffic scheduling to adapt traffic pattern changes.

The RCP reformats a station BTP in a more convenient form for the baseband processor and generates beam forming network (BFN) control data.

5.3.2.2 Acquisition and Synchronization Processor

The BBP measures the transmit timing error of a station orderwire burst and sends it to the MCS via the down-link orderwire channel. Figure 5-34 shows processing steps for acquisition and synchronization data. The measured data are analyzed by the ASP and retransmitted to the satellite along with aperture data for burst detection on the satellite. The aperture data are

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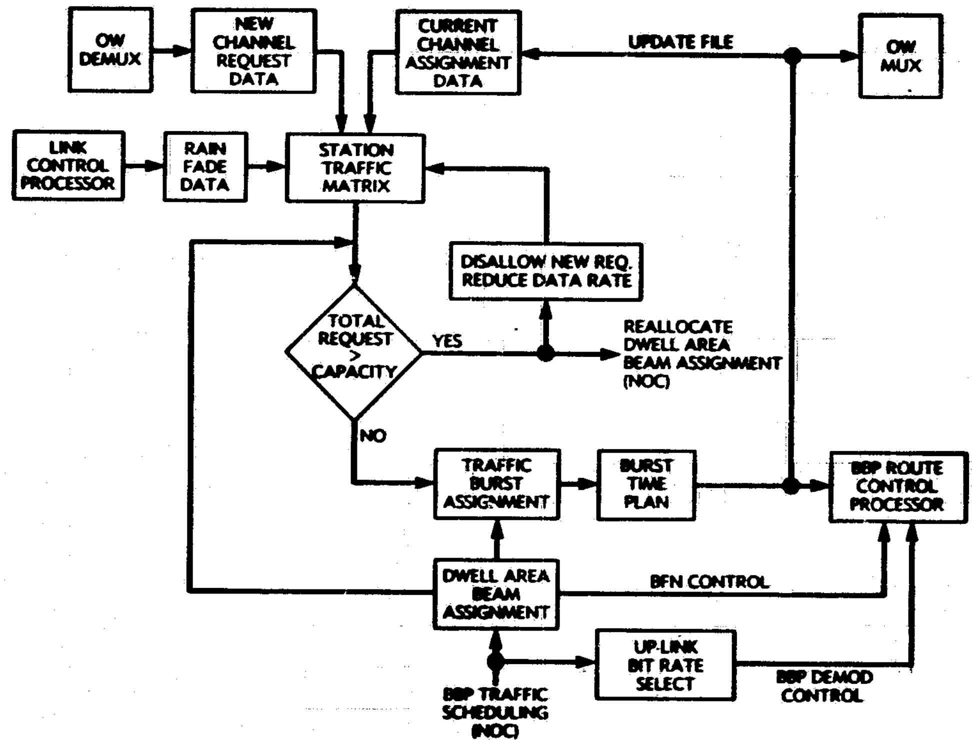

Figure 5-33. CPS Ch.:nnel Assignment Processing

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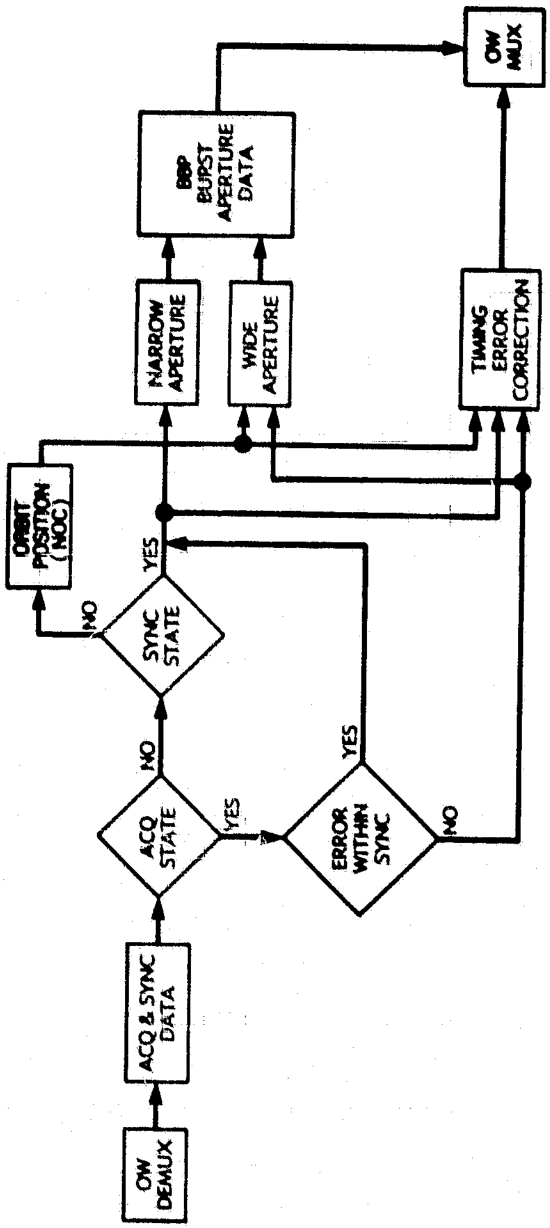

Figure 5-34. Acquisition and Synchronization Processing

stored in an alternate aperture memory on the satellite which is activated in the following control frame. Thus, new aperture window timing coincides with the arrival times of CPS bursts with corrected transmit timing.

5.3.2.3 Alarm Processors

The SAP and BAP process status and alarm data sent from the CPS stations and on-board baseband processor, respectively.

5.3.3 NETWORK OPERATIONS CENTER

The NOC performs extensive data processing and interacts with the network controllers and local traffic processors. Figure 5-35 illustrates typical data processing functions.

The SS-TDMA traffic scheduling task generates a switch-state assignment for the on-board IF switch matrix and a burst time plan for trunking stations. The CPS traffic scheduling task produces necessary channel assignment data for the baseband processor and CPS stations. To accommodate ever changing channel requests and sudden rain fade conditions, the CAP of the network controller executes a simple burst scheduling algorithm; however, a major channel allocation is the responsibility of the NOC.

Other tasks of the NOC are link analysis, station and BBP status processing, satellite range calculation for open-loop acquisition, and computation of on-board clock correction data.

The data processing equipment configuration of the NOC is shown in Figure 5-36, and its equipment list is given in Table 5-5.

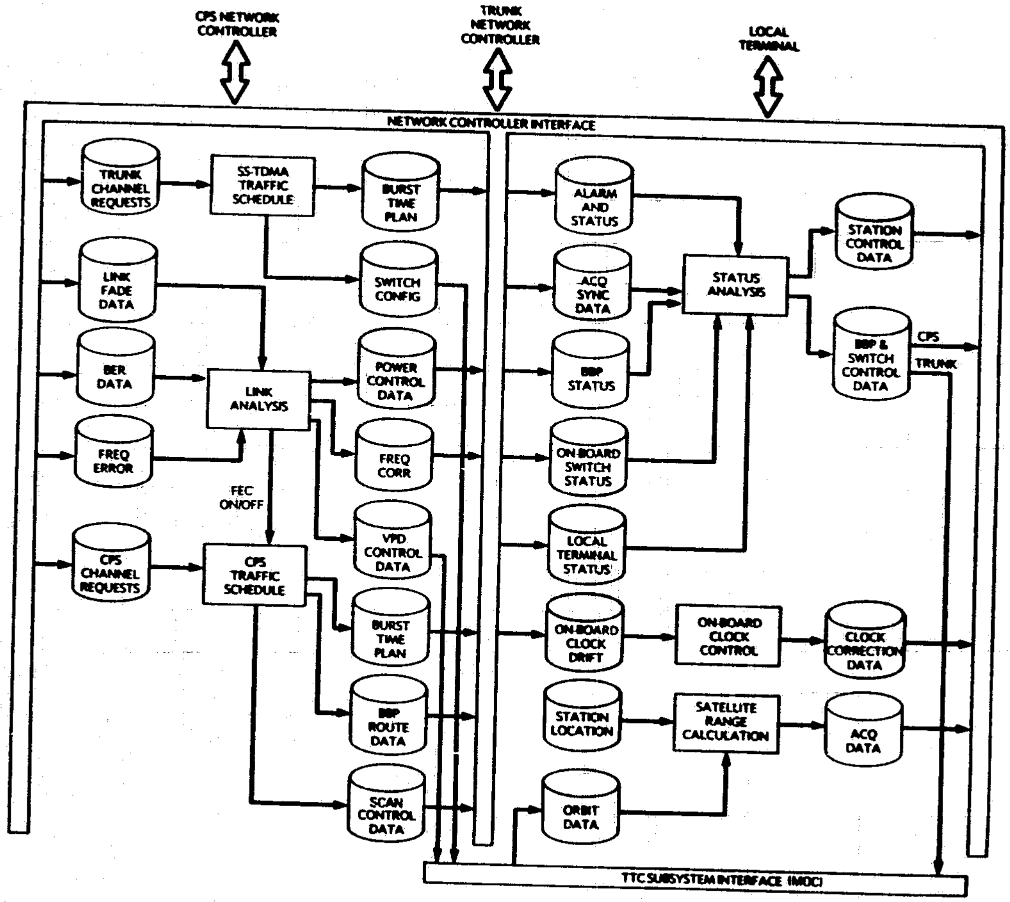

Figure 5-35. Network Operations Center Data Processing

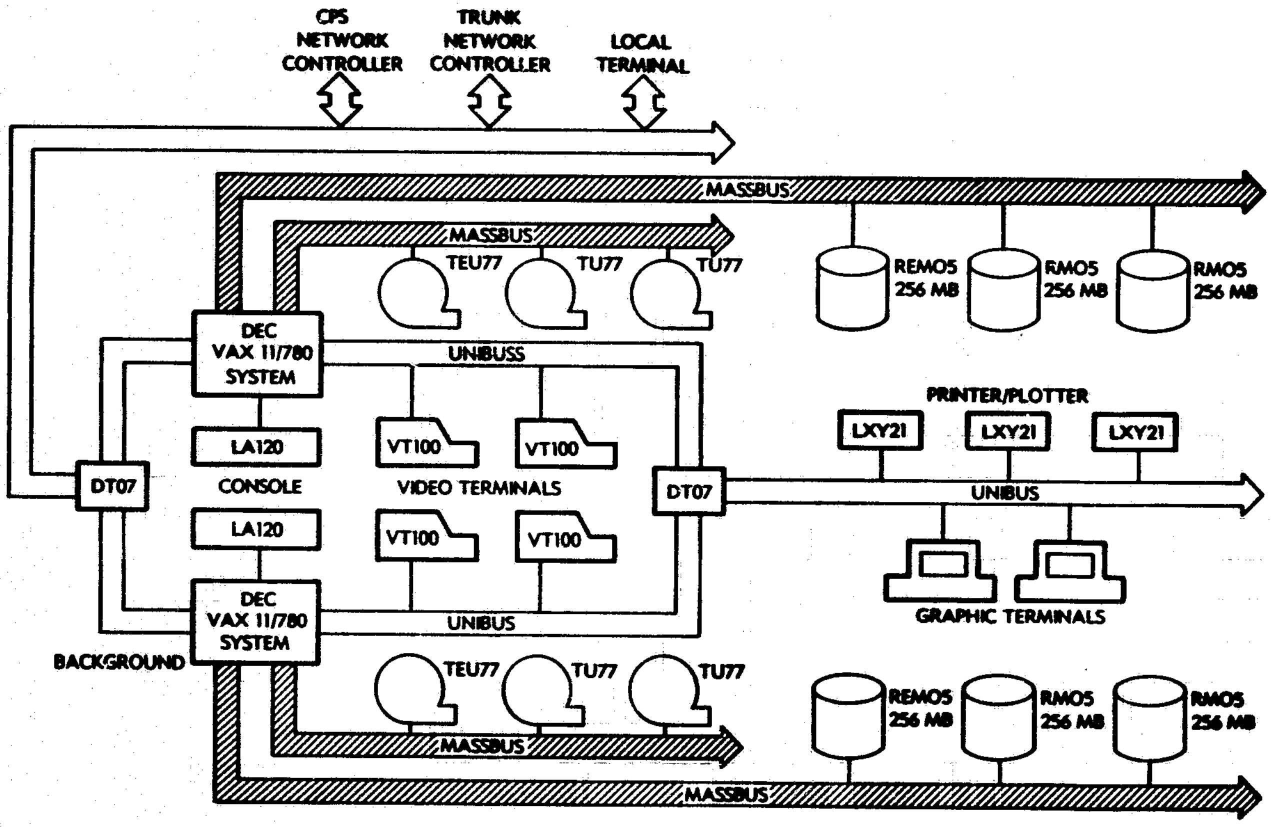

Figure 5-36. NOC Data Processing Equipment

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Table 5-5. Network Operations Center Equipment List

Quantity	Device
2	SV-AXDBC-CA. DEC VAX-11/780 System Contains 1 VAX-11/780 CPU 1 2-MB ECC Memory 1 REM05 256-MB Disk drive with massbus adapter (MBA) 1 TEU77 (125 in/s, 800/1600 b/in) Tape transport with MBA 1 DZ11-A 8-Line asynchronous multiplexer 1 LA120 Console terminal
2	RM05-AA 256-MB Single access removable disk pack drive
2	RM05-AC 256-MB Single access removable disk pack drive
2	DT07-BA Unibus switch
2	DW780-AA Unibus adapter
4	TU77-AF Tape transport unit
6	VT100-AA Video display terminal
2	VS11-AA Graphic display unit
3	LXY21-XX Printer (600 lines/min)/plotter (320 lines/min)

6. NETWORK CONTROL SYSTEM COST

The network control system of the MCS is shown in Figure 6-1. It consists of two types of network controllers with corresponding burst processors, a common diversity control unit, and a link monitor system. A fully redundant configuration is employed to achieve high reliability. The network operations center, as described in the previous section, possesses a backup computer for redundancy. Cost breakdown of the network control system based on the above configuration is shown in Table 6-1. The total cost is approximately $30.80 million. A large portion (about 55 percent) of this cost is allocated for software development. Breakdown of the software development cost is shown in Table 6-2.

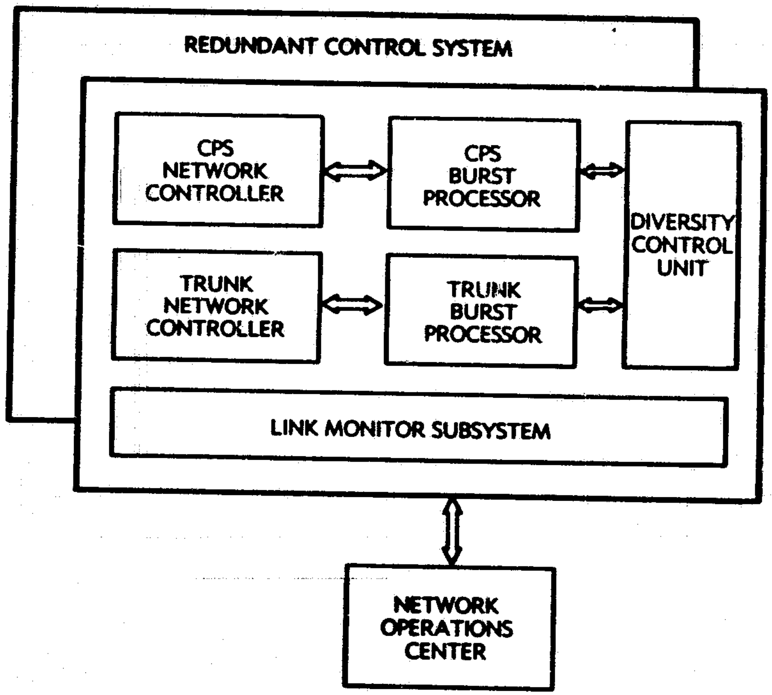

Figure 6-1. Network Control System Configuration

Table 6-1. Network Control System Cost in 1982 ($M)

Diversity control unit	0.23
Trunk network control system	1.77
Burst processor (0.62)	
Network controller (1.15)	
CPS Network Control System	2.75
Burst processor (0.81)	
Network controller (1.94)	
Link monitor subsystem	0.47
Redundant control system	1.21
Network operations center	3.24
Installation and test	0.12
Spare parts	0.27
	10.06
Overhead (150 percent)	15.09
Parts and components	1.63
	26.78
Fee (15 percent)	4.02
Total	30.80

Table 6-2. Software Development Cost in 1982 ($M)

Trunk network control system	1.23
CPS network control system	1.96
Link monitor subsystem	0.14
Network operations center	2.59
	5.92
Overhead (150 percent)	8.88
	14.80
Fee (15 percent)	2.22
Total	17.02

7. CONCLUSIONS

The experimental system explores the use of 30/20-GHz frequency bands for future communications satellites and demonstrates the technological feasibility of advanced communications processing concepts. The network control system establishes a communications link between the spacecraft and ground stations by means of accurate orderwire message exchanges and precise network timing control. The following conclusions are drawn from this study:

a. Centralized network control provides reliable and cost-effective satellite network operation.

b. A network control architecture can be efficiently designed to perform all the necessary experiments, while allowing for possible planned expansion to an operational system.

c. The master control station requires reliable hardware and software to monitor and control network operation as well as good fault detection and isolation capabilities. A large portion (about 55 percent) of the network control system development cost is allocated for the software development.

d. Demand-assignment processing in the CPS network is one of the most time critical software functions. For a large number of earth stations (of the order of thousands), it is desirable to distribute processing among the MCS and CPS earth stations such that the MCS is responsible for the space segment channel allocation, and the channel allocation within a traffic burst is performed by the participating earth stations.

e. Network operation and spacecraft control are closely interrelated because of the needs for implementing demand-assignment processing for the baseband processor and controlling rain fade effect via adaptive power control and FEC.

f. Selection of a modulation technique must be further investigated. Quaternary phase shift keying (QPSK) has some advantage over serial minimum shift keying (SMSK), since it can easily accommodate one-half rate reduction operation for an additional CPS link margin (if desired). Alternatively, SMSK produces lower adjacent transponder interference which may result in better link margin in the presence or absence of fades. Further tradeoffs are required, including implementation complexity, reliability, and cost.

g. A 30-GHz on-board beacon appears to be desirable for accurate up-link rain fade measurement.

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